Quantum enhanced magnetometer and squeezed state of light tunable filter

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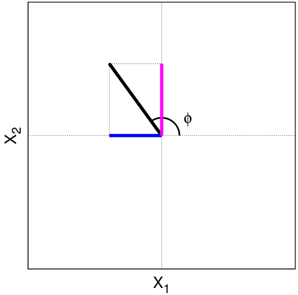
Transition from classical to quantum field

Classical analog

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

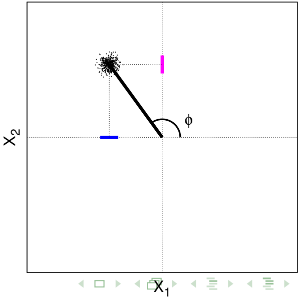
$$E(\phi) \quad = \quad |a|e^{-i\phi} = X_1 + iX_2$$



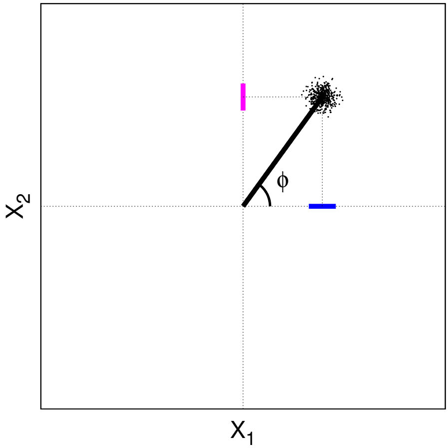
Quantum approach

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

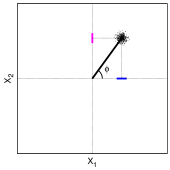
$$\hat{E}(\phi) \quad = \quad \hat{X}_1 + i\hat{X}_2$$



Squeezed quantum states zoo

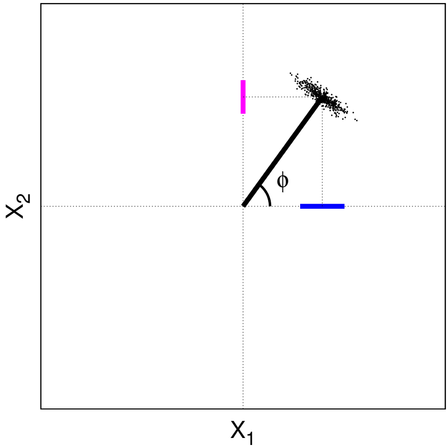


Unsqueezed coherent

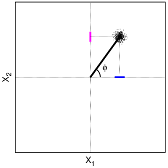


Notice $\Delta X_1 \Delta X_2 \geq \frac{1}{4}$

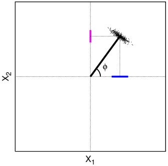
Squeezed quantum states zoo



Unsqueezed coherent



Amplitude squeezed



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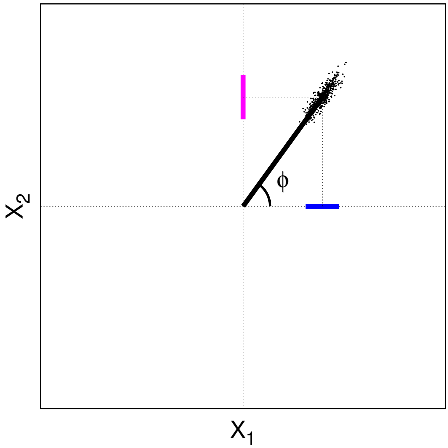
Squeezed quantum states zoo



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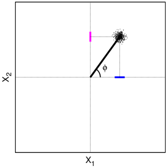
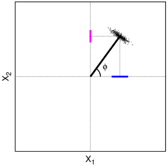
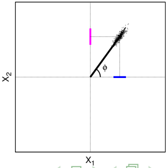


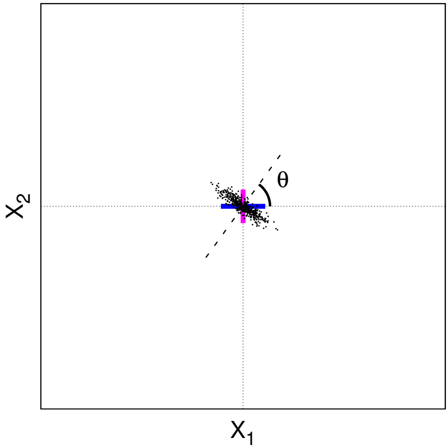
Amplitude squeezed



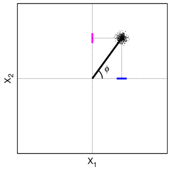
Phase squeezed



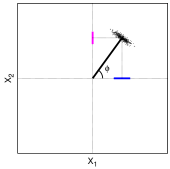
Squeezed quantum states zoo



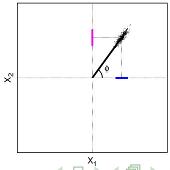
Unsqueezed coherent



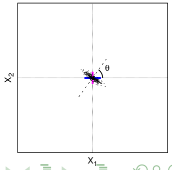
Amplitude squeezed



Phase squeezed

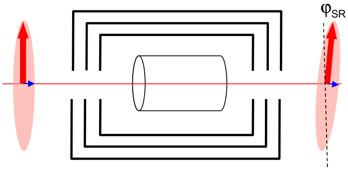


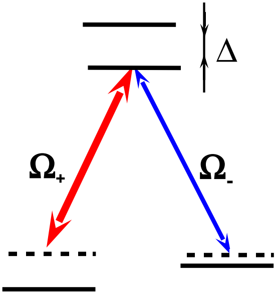
Vacuum squeezed



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

Self-rotation of elliptical polarization in atomic medium

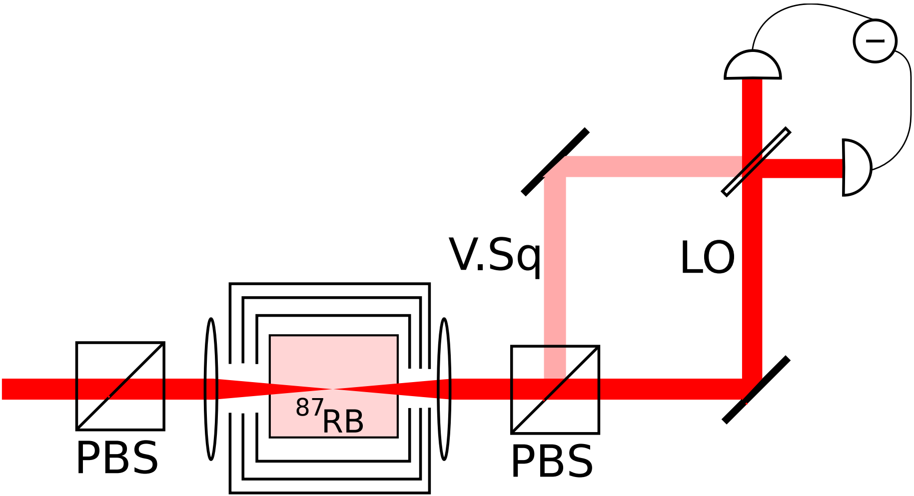




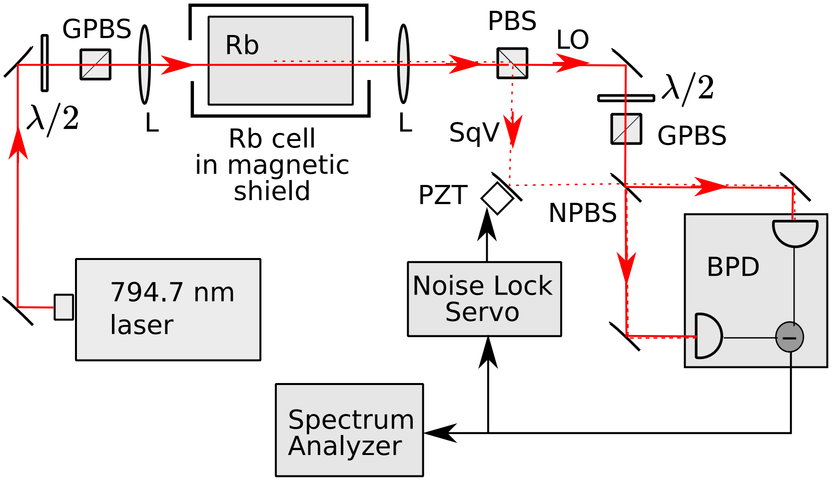
A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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

Simplified setup



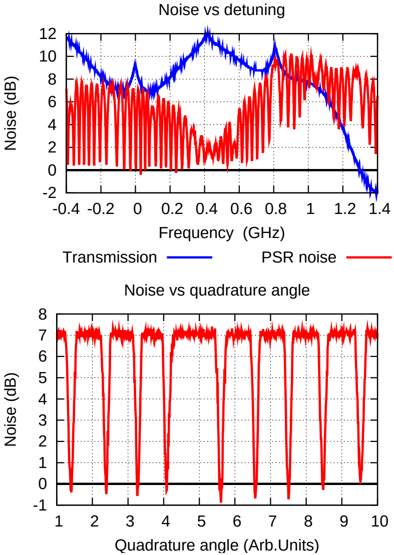
Setup



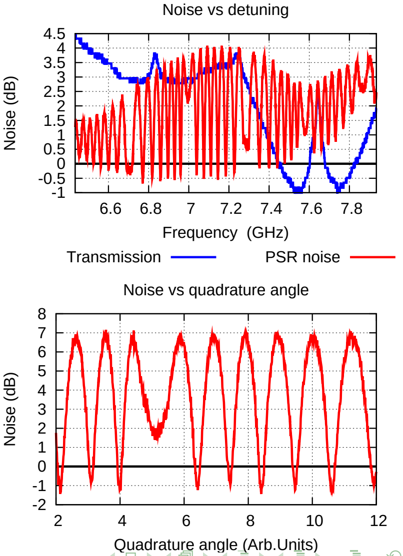
GPBS
Rb
PBS
LO
$\lambda/2$
$\lambda/2$
L
Rb cell
in magnetic
shield
L
SqV
GPBS
PZT
NPBS
BPD
794.7 nm
laser
Noise Lock
Servo
Spectrum
Analyzer

Noise contrast vs detuning in hot ^{87}Rb vacuum cell

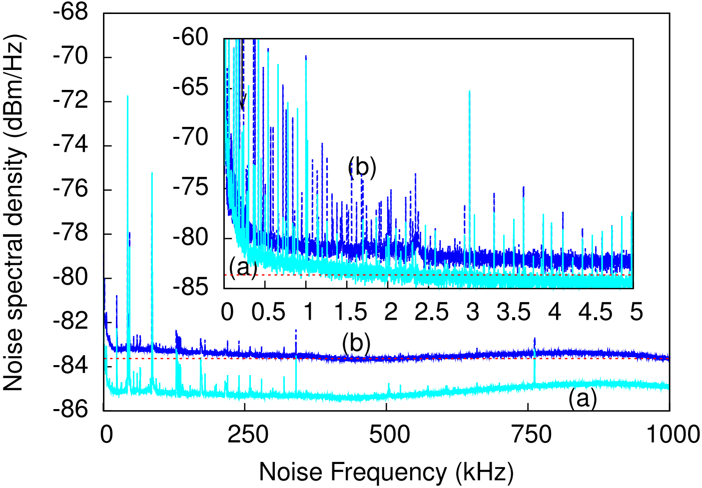
$F_g = 2 \rightarrow F_e = 1, 2$



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

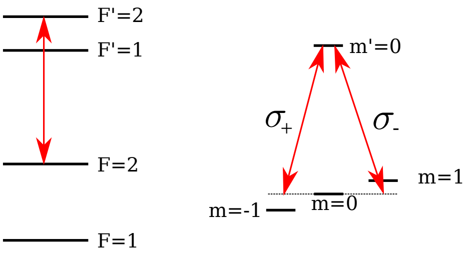


Atomic low frequency squeezing source

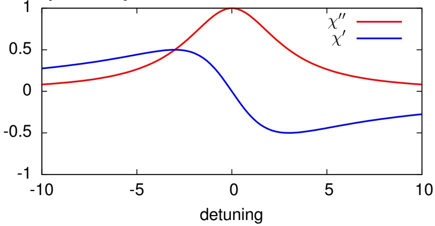


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



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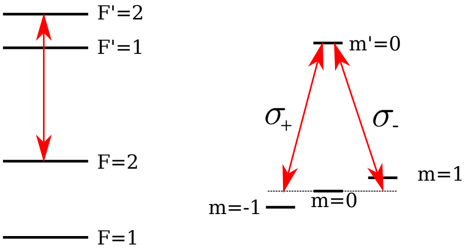
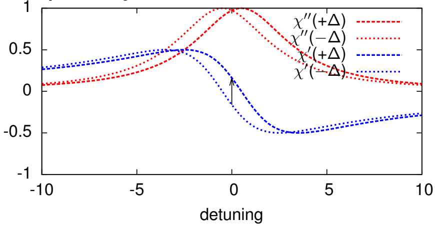
^{87}Rb D$_1$ line



Susceptibility vs B



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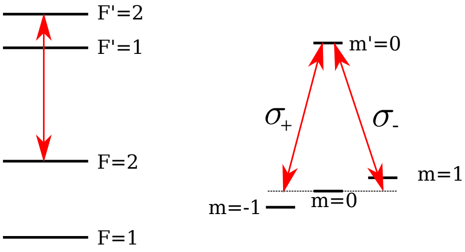

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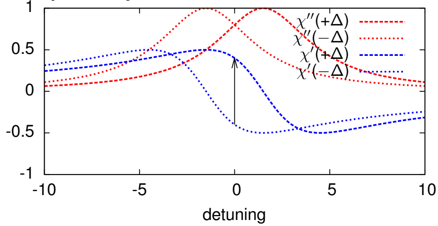

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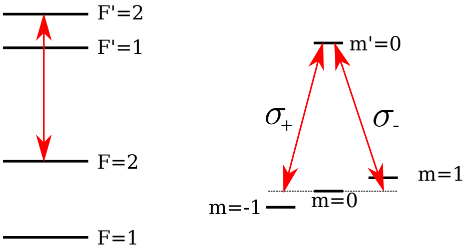
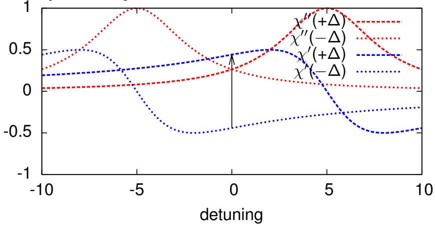
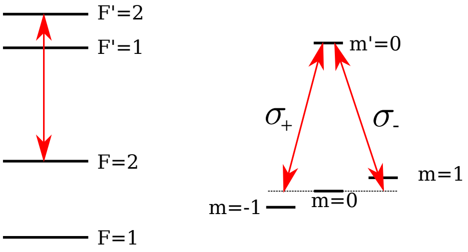


Susceptibility vs B



Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



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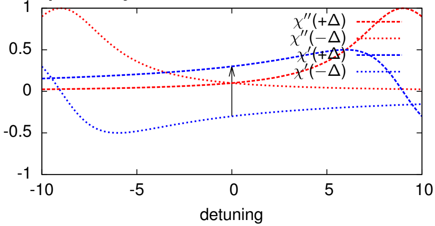

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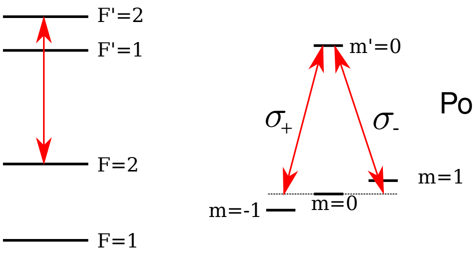
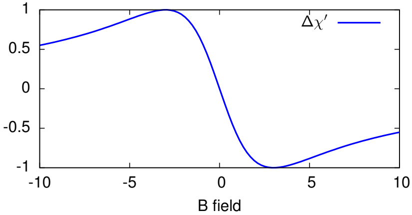
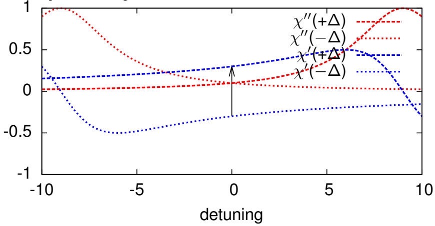
^{87}Rb D_1 line



Polarization rotation vs B

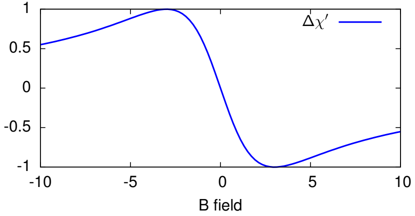


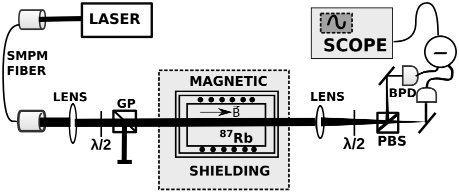
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

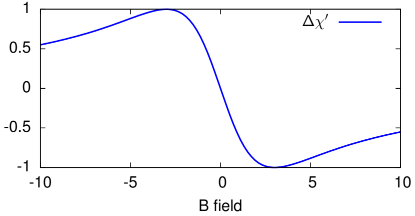
Naive model of rotation

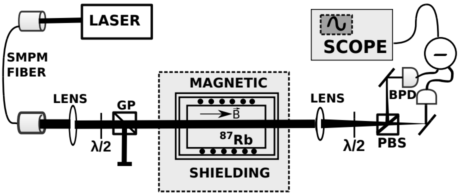




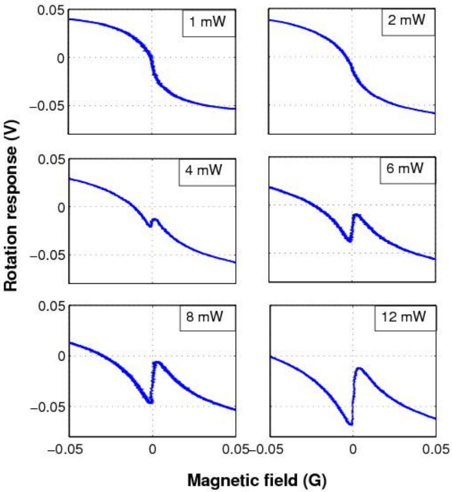
Experiment

Naive model of rotation

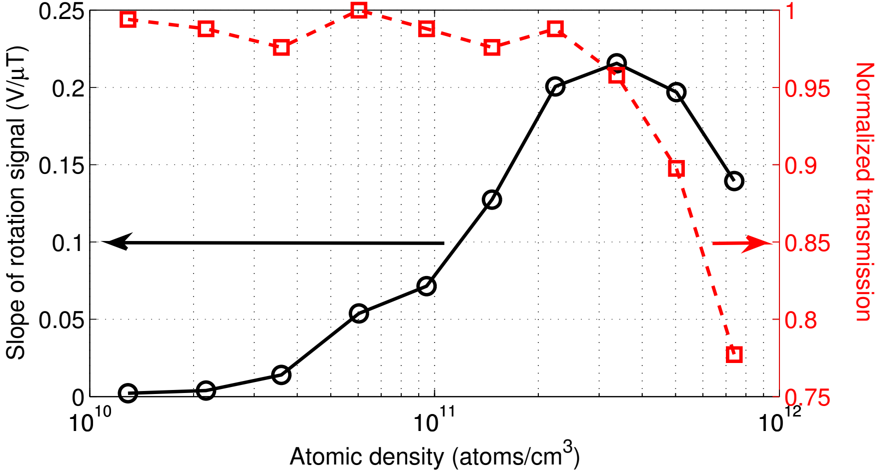




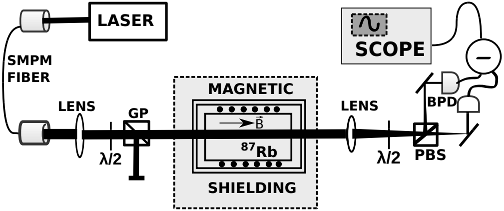
Experiment

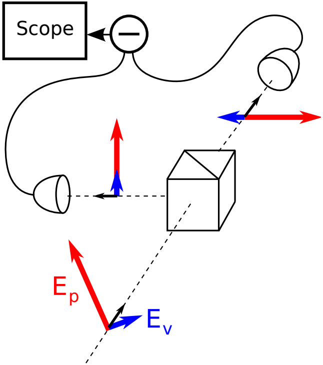


Magnetometer response vs atomic density



Shot noise limit of the magnetometer



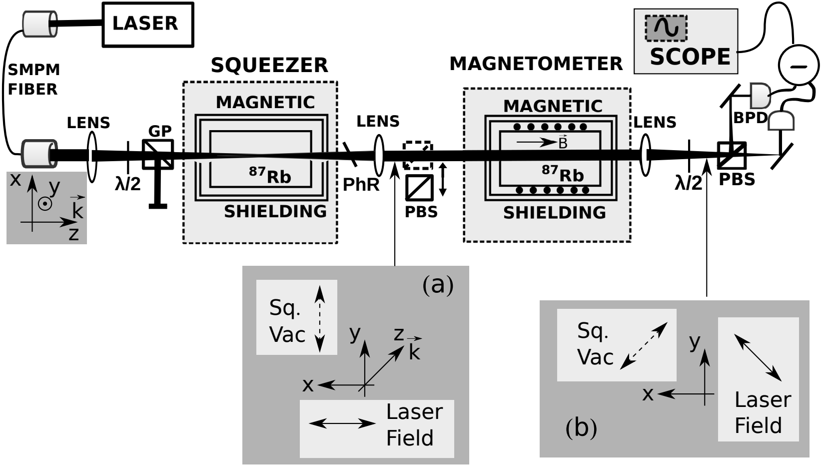


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_pE_v$$

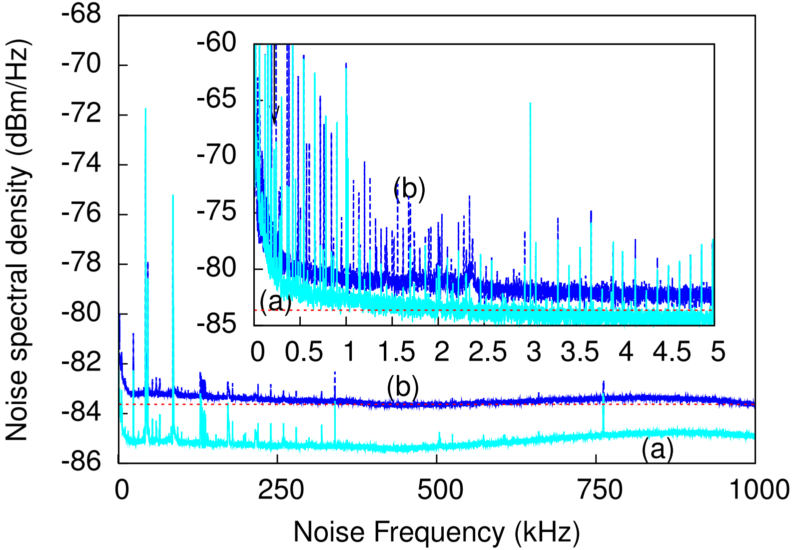
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

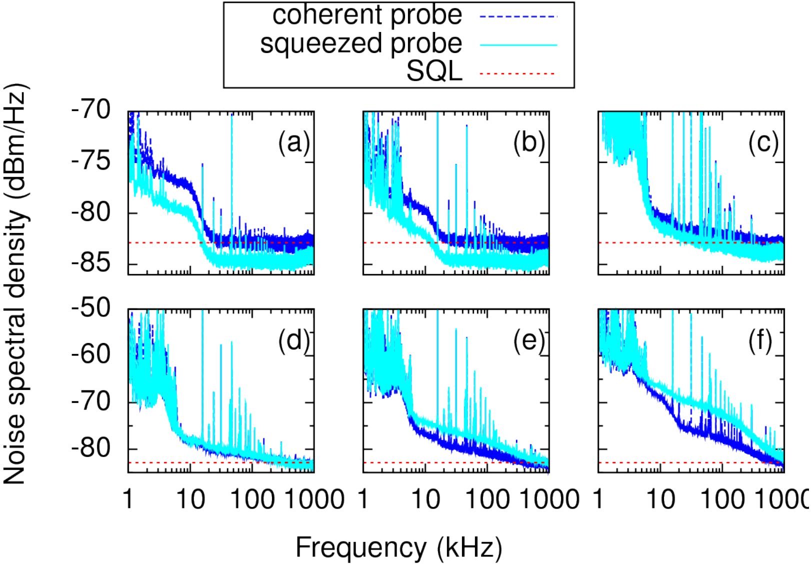


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

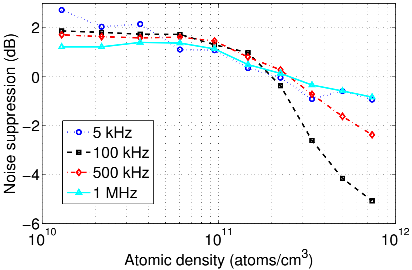


Magnetometer noise spectra

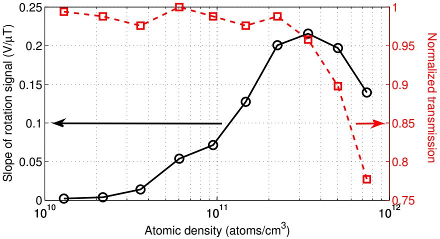


Noise suppression and response vs atomic density

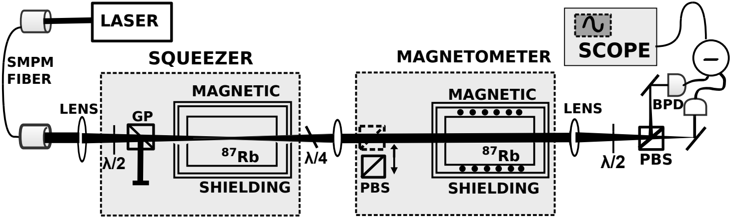
Noise suppression

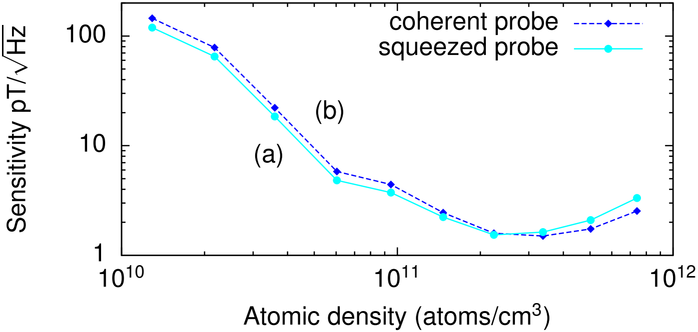


Response



Magnetometer with squeezing enhancement

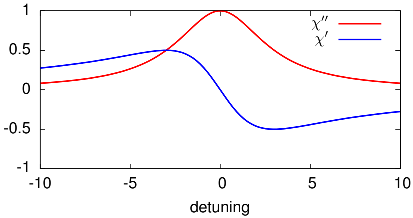




Light group velocity expression

Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Susceptibility

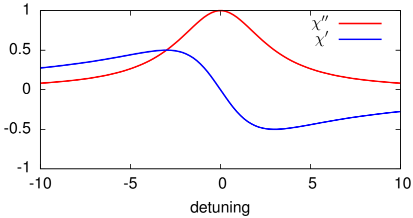


Rotation vs B field

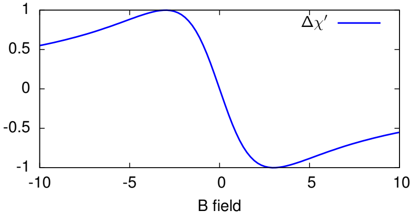
Light group velocity expression

Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Susceptibility



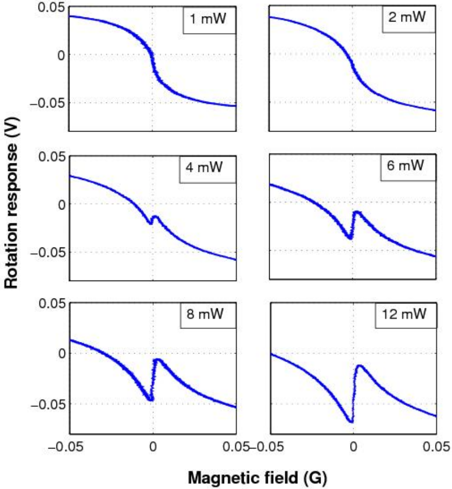
Rotation vs B field



Light group velocity estimate

Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Delay $\tau = \frac{L}{v_g} \sim \frac{\partial n}{\partial \omega} \sim \frac{\partial R}{\partial B}$



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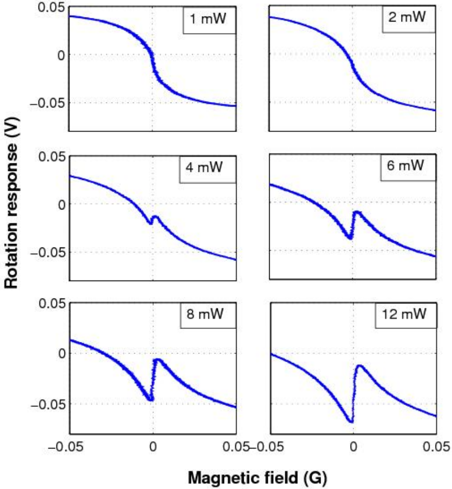
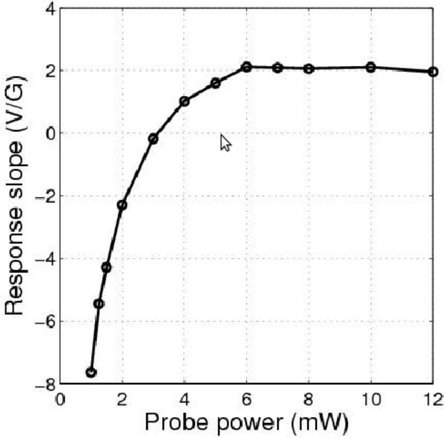
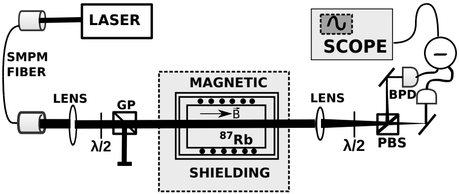
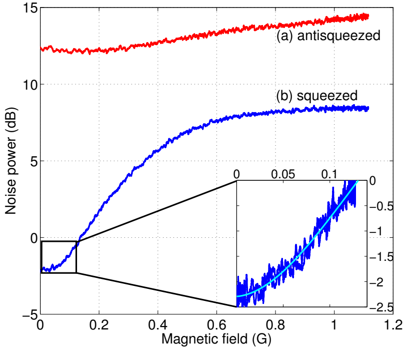




Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz





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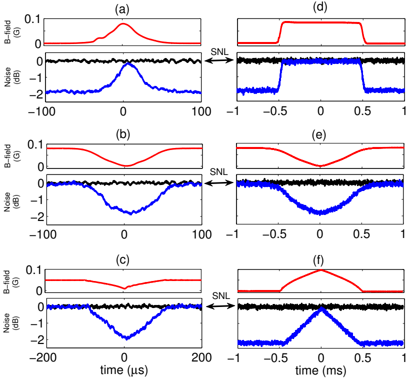
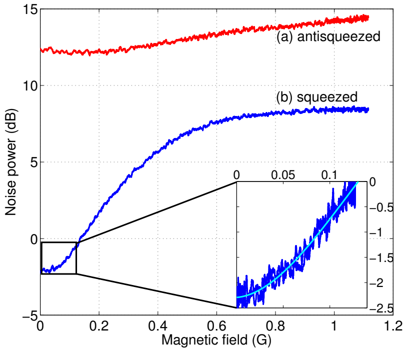
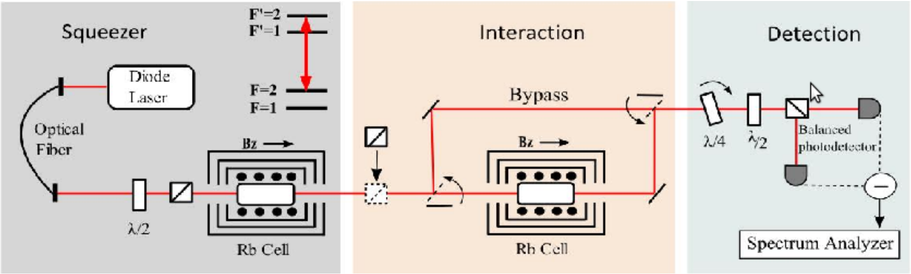
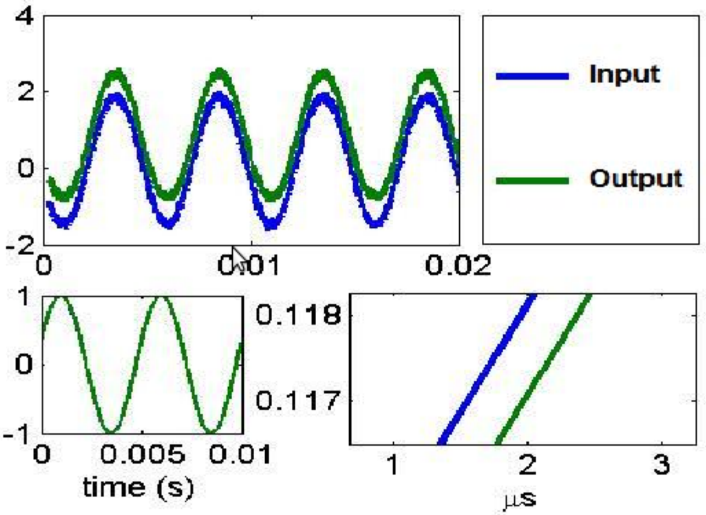




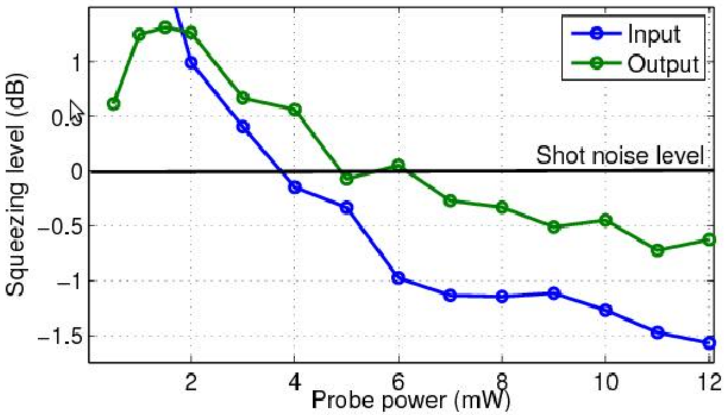
Time advancement setup



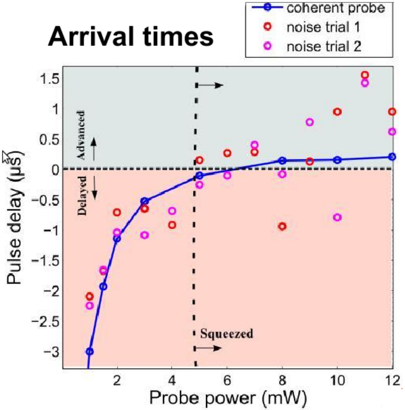
Squeezing modulation and time advancement



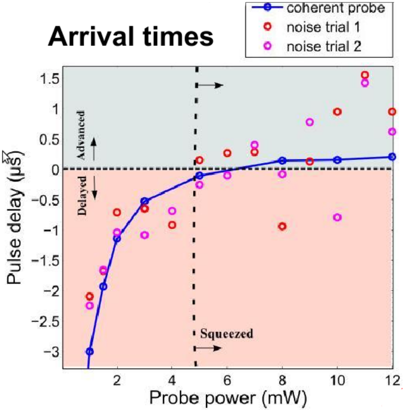
Squeezing after advancement cell

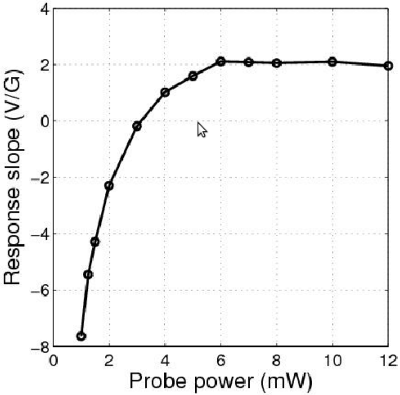


Advancement vs power



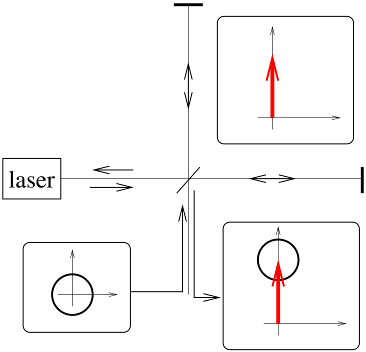
Advancement vs power



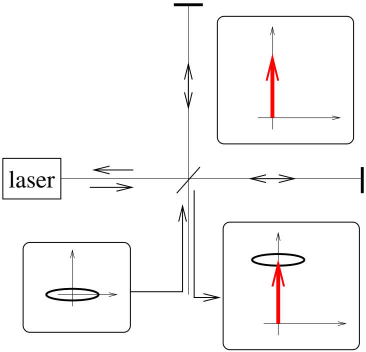


Quantum limited interferometers revisited

Vacuum input



Squeezed input



Limiting noise - Quantum Optical noise

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

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shot noise

Uncertainty in number of photons

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

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Photons impart momentum to mirrors

$$h \sim \sqrt{\frac{P}{M^2 f^4}} \qquad (3)$$

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radiation pressure noise

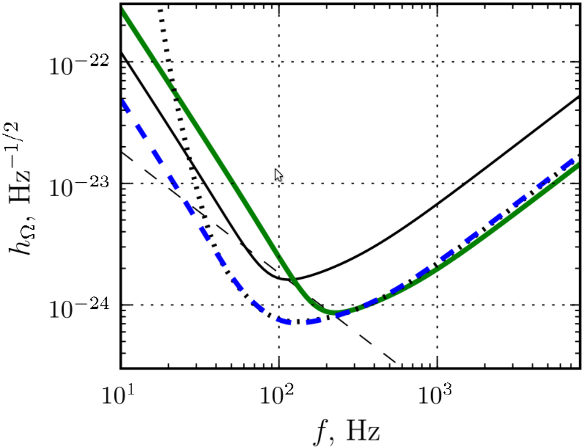
Photons impart momentum to mirrors

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

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

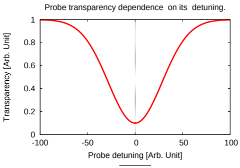
Interferometer sensitivity improvement with squeezing

Projected advanced LIGO sensitivity

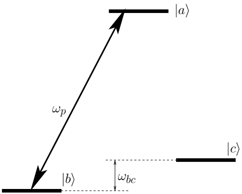


F. Ya. Khalili Phys. Rev. D 81, 122002 (2010)

EIT filter

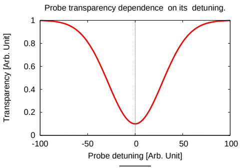


Probe transparency dependence on its detuning.
Transparency [Arb. Unit]
1
0.8
0.6
0.4
0.2
0
-100
-50
0
50
100
Probe detuning [Arb. Unit]



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

EIT filter


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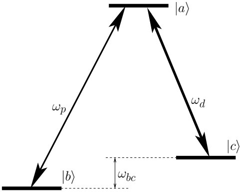
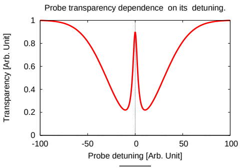
100


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


Probe transparency dependence on its detuning.
Transparency [Arb. Unit]
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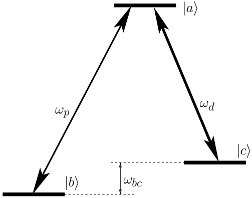
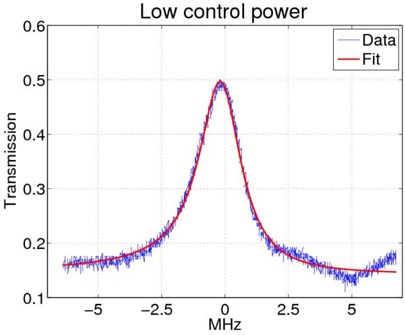
Squeezing and EIT filter

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

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

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





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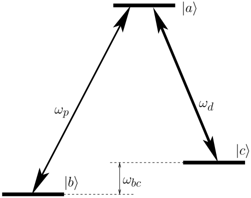

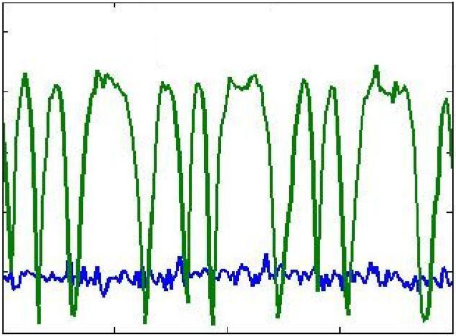

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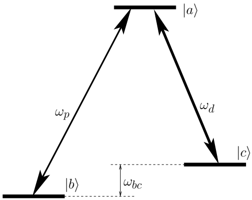
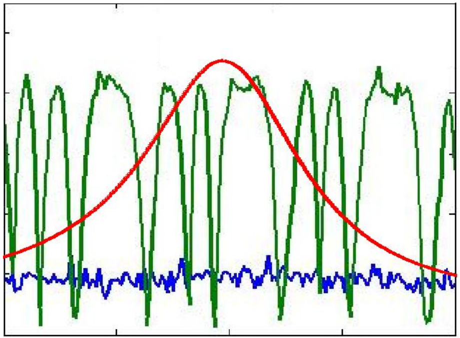
$$\begin{aligned} \varphi_\pm &= \frac{1}{2}(\Theta_+ \pm \Theta_-) \\ A_\pm &= \frac{1}{2}(T_+ \pm T_-) \end{aligned}$$





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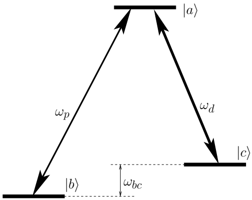
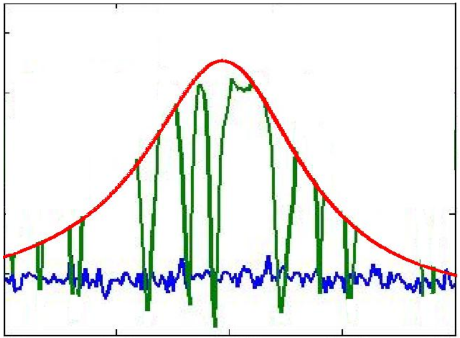
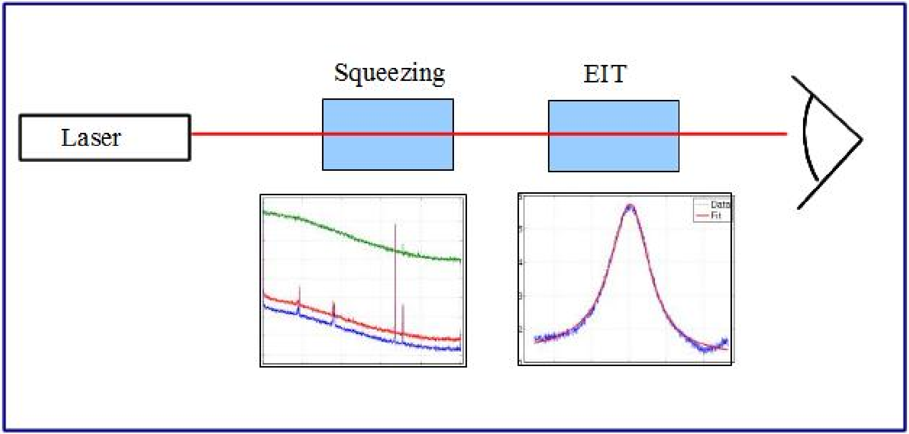
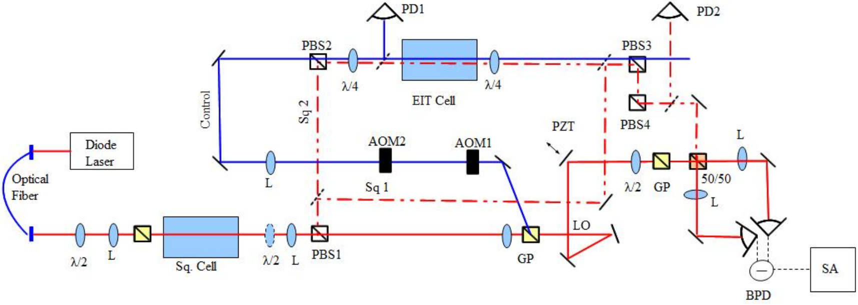




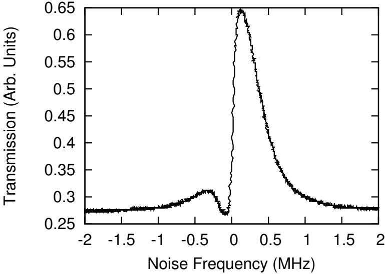
Squeezing and EIT filter setup



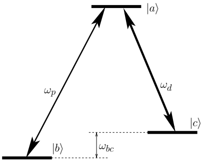
Squeezing and EIT filter setup



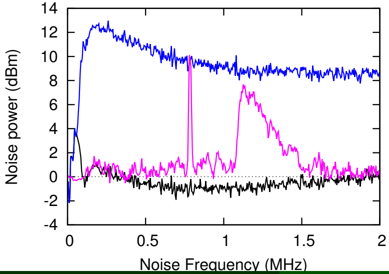
EIT filter and measurements without light

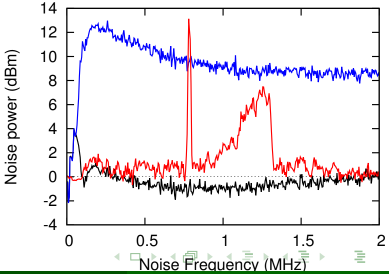


Coherent signal

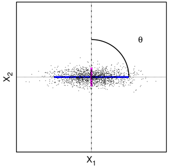


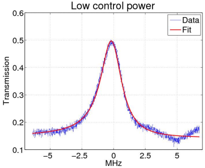
Signal in the noise quadratures

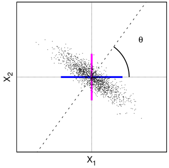




Squeezing angle rotation

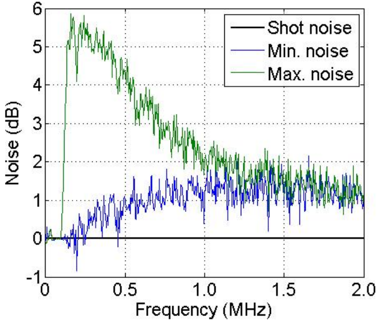




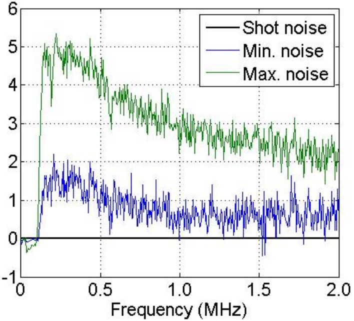


$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} \cos^2\varphi_+ & \sin^2\varphi_+ \\ \sin^2\varphi_+ & \cos^2\varphi_+ \end{pmatrix} \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right]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

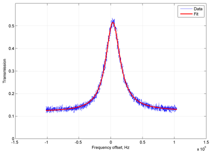
Locked at 300kHz

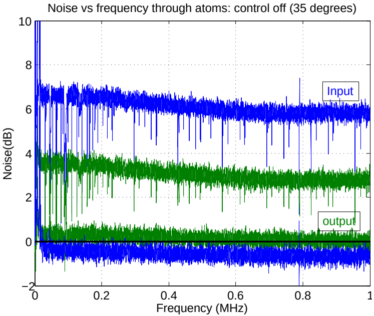


Locked at 1200kHz

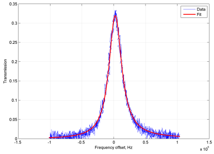


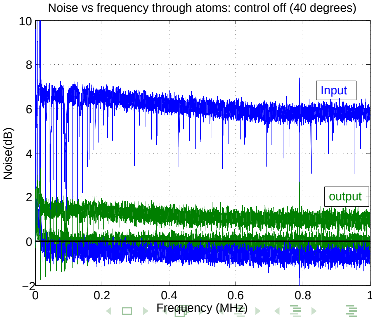
T=35°C, no control transmission 42%





T=40°C, no control transmission 17%





T=35°C, no control
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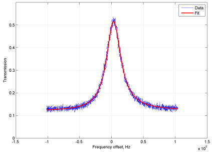

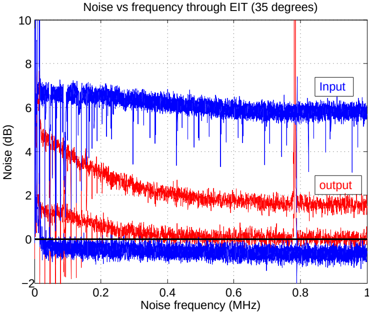

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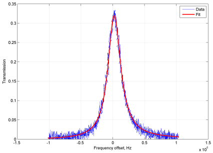
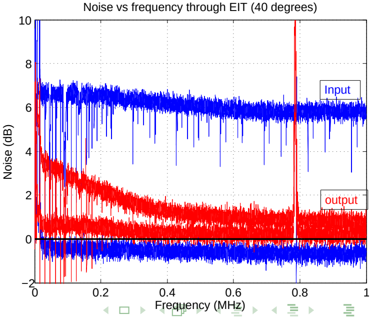
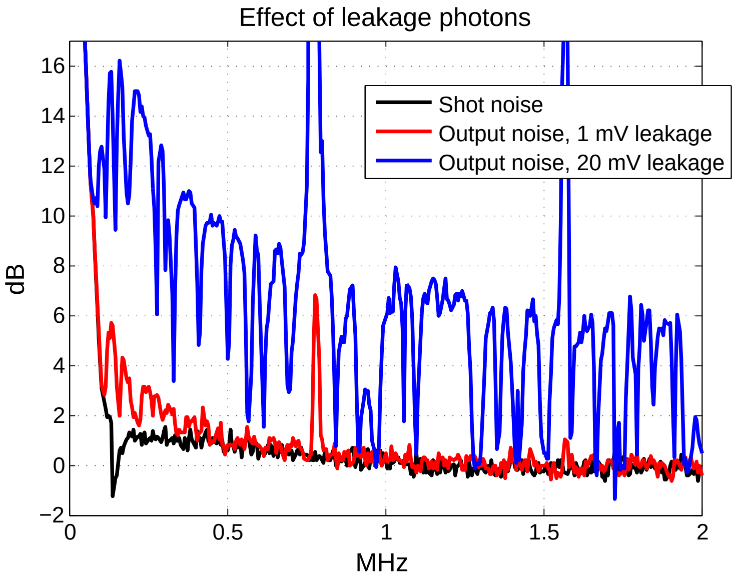


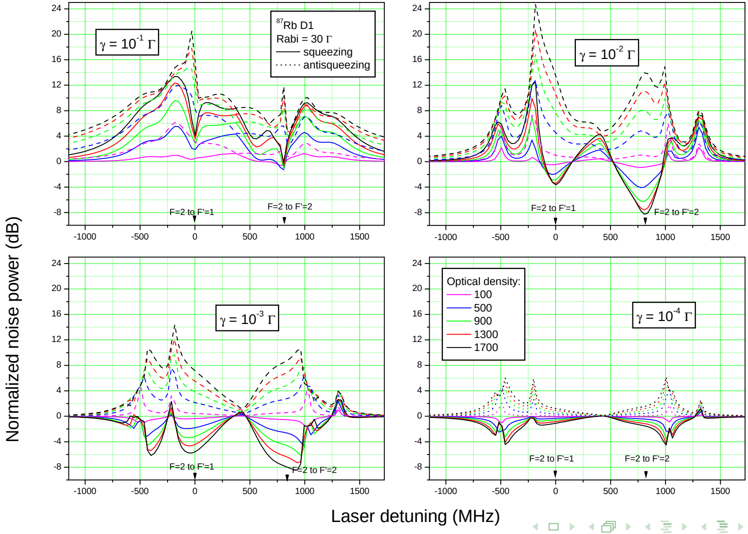


Excess noise and leakage



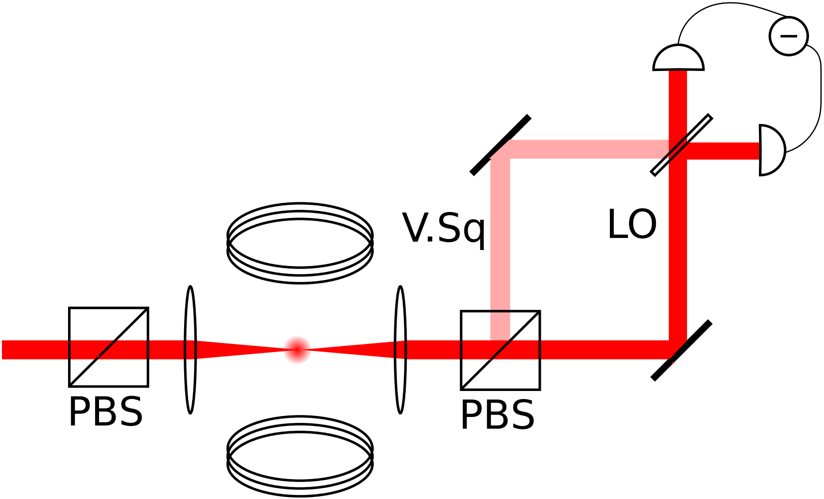
Theoretical prediction for MOT squeezing with ^{87}Rb

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

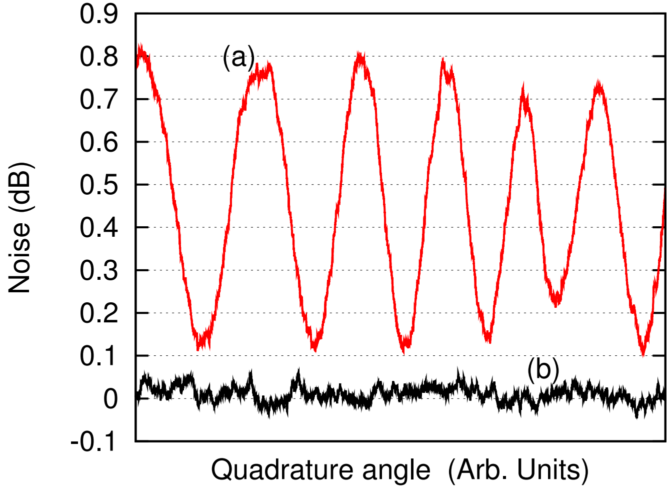


MOT squeezer

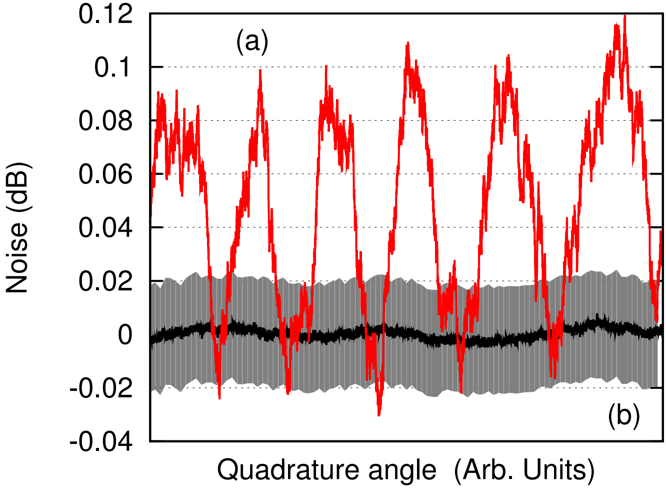
Cloud size =1 mm, T = 200 μK, N = 7 $\times$ 10^9 1/cm^3,
OD = 2, beam size = 0.1 mm, 10^5 interacting atoms



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

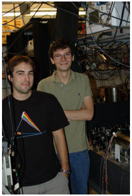


Squeezing in MOT with ^{87}Rb $F_g = 2 \to F_e = 1$



People

Travis Horrom and Gleb Romanov



Robinjeet Singh, LSU

Irina Novikova

Jonathan P. Dowling, LSU

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
- First demonstration of superluminal squeezing propagation with $v_g = c/2000$ or time advancement of 0.5 μS

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”, arXiv:1204.3967.

Support from