# Optical magnetometer with quantum enhancement.

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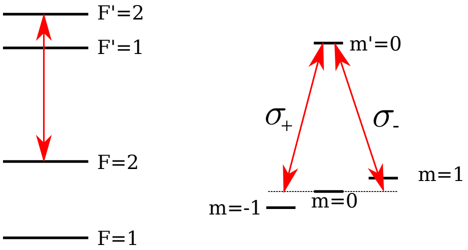
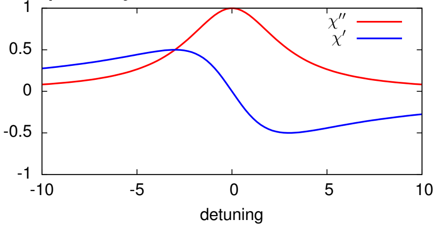
21st International Laser Physics Workshop in Calgary, Canada.
July 24, 2012

# Optical magnetometer based on Faraday effect

$^{87}$Rb D$_1$ line




Susceptibility vs B



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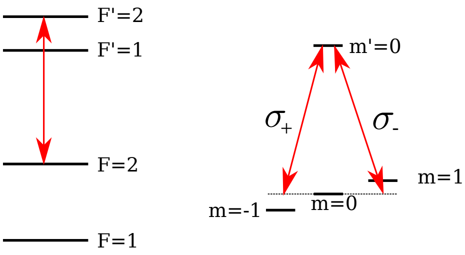


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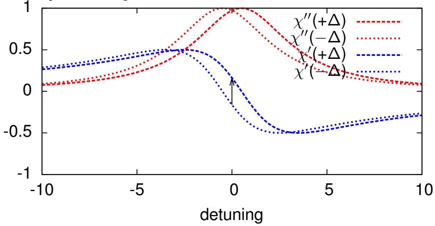

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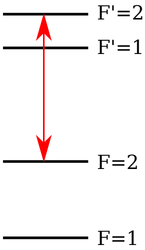


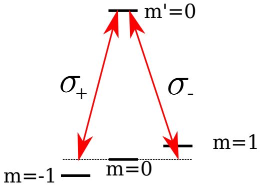


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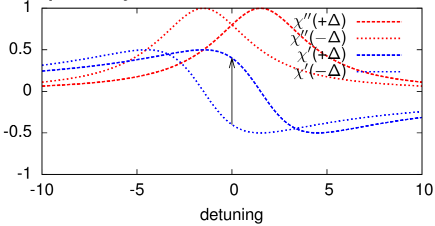

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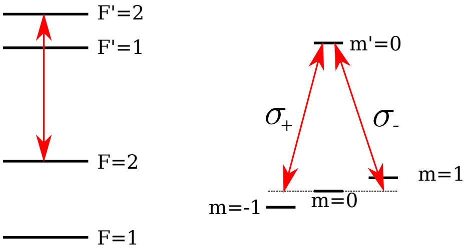
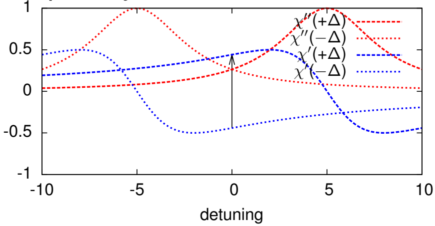



Susceptibility vs B



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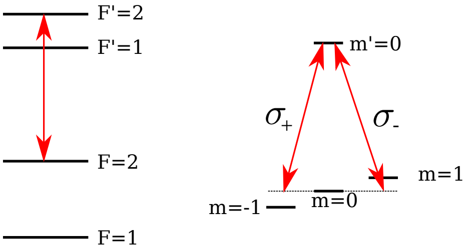


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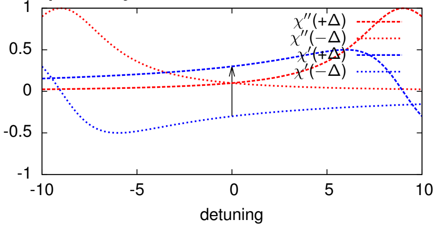

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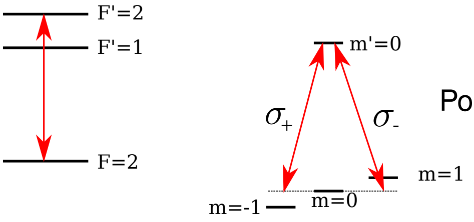
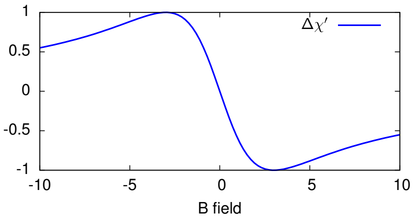



## Polarization rotation vs B

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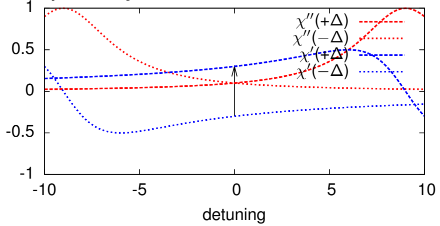
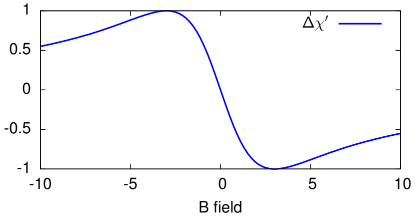
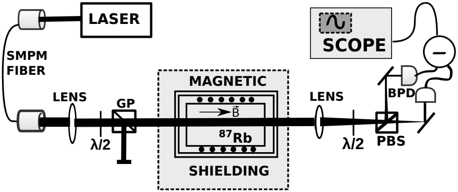


# Optical magnetometer and non linear Faraday effect

## Naive model of rotation

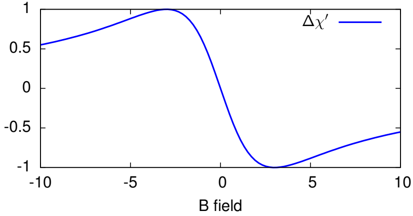


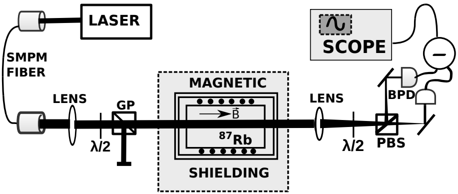




## Experiment

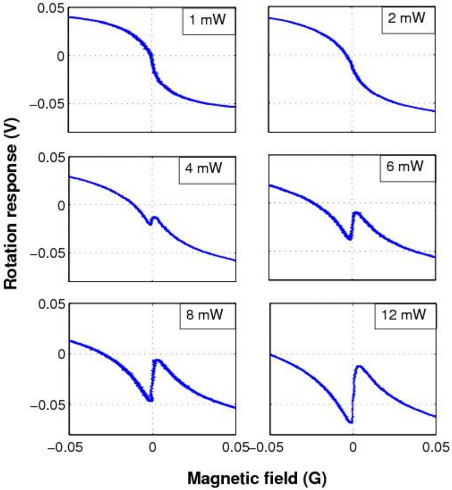
# Optical magnetometer and non linear Faraday effect

## Naive model of rotation

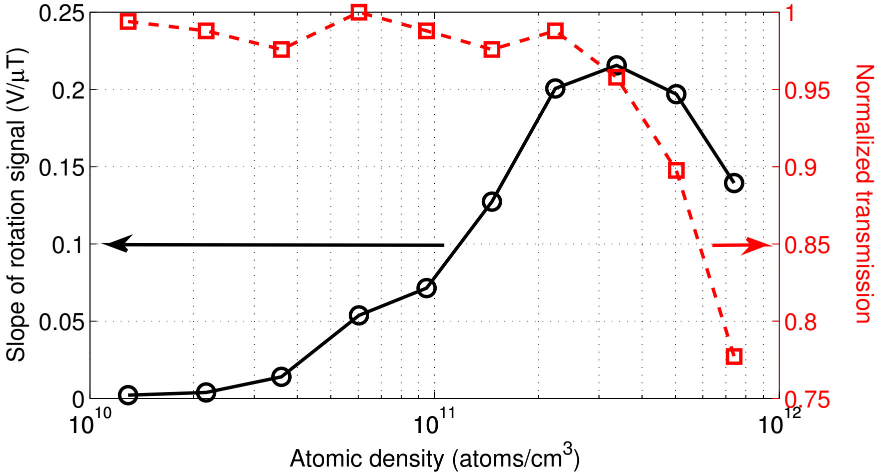


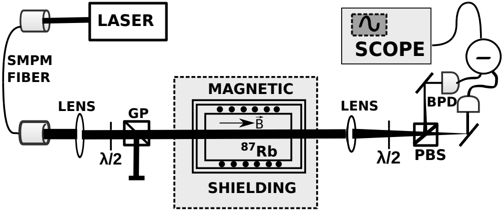

## Experiment

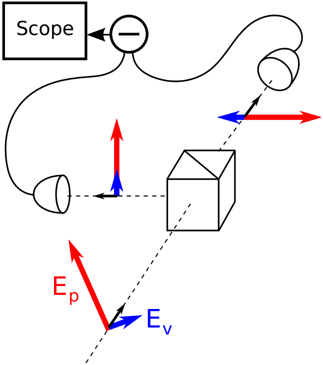


# Magnetometer response vs atomic density



# Shot noise limit of the magnetometer




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

# 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

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## Optics equivalent strict definition

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

# Transition from classical to quantum field

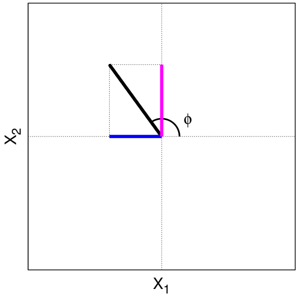
Classical analog

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

Quantum approach

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

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

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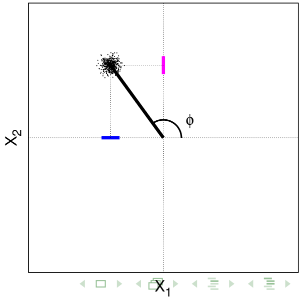
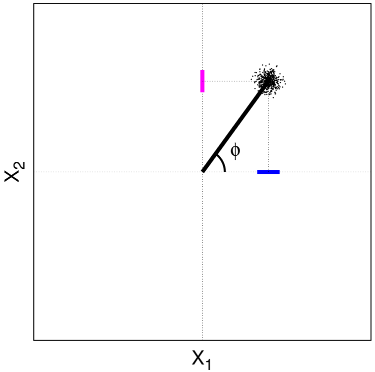
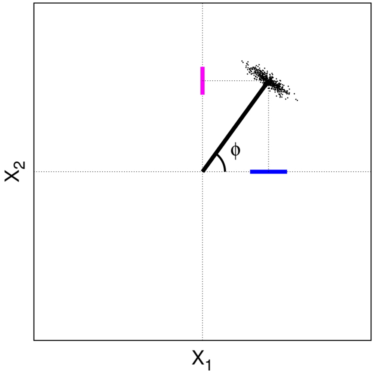


# Minimum uncertainty (coherent) states

Coherent state




Squeezed state

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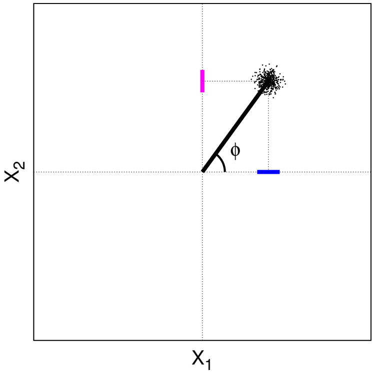


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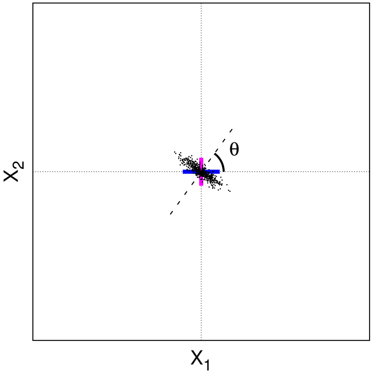


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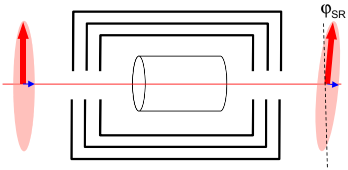
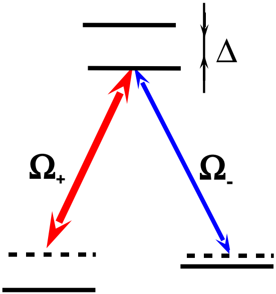
# Self-rotation of elliptical polarization in atomic medium

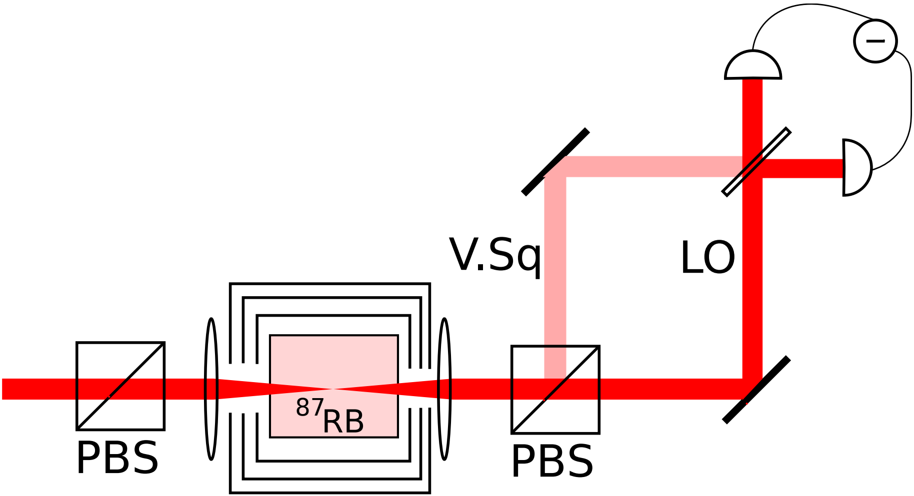



$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

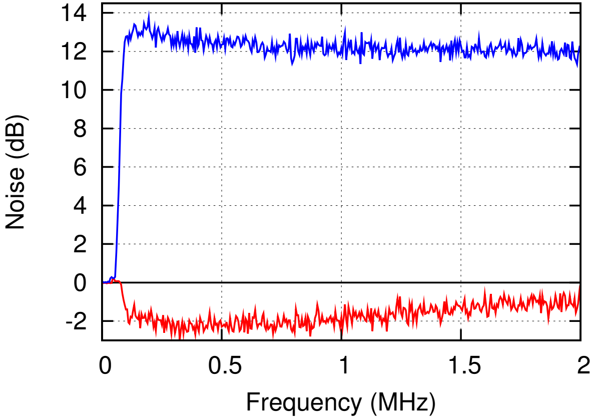
- **theory :** A.B. Matsko et al., PRA 66, 043815 (2002)
- **experiment:** J. Ries, B. Brezger, and A. I. Lvovsky, Experimental vacuum squeezing in rubidium vapor via self-rotation, PRA **68**, 025801 (2003).

# Setup



# Maximally squeezed spectrum with $^{87}$Rb

W&M team. $^{87}$Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65° C



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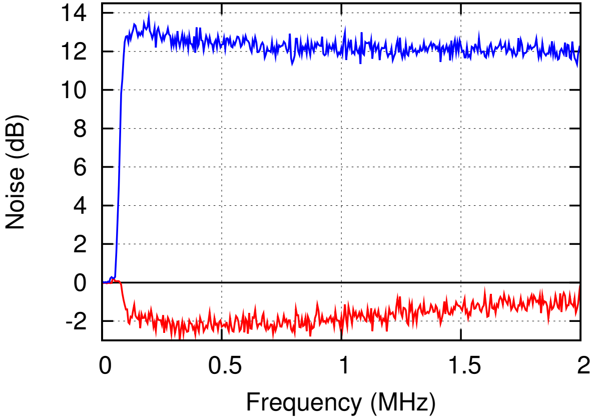
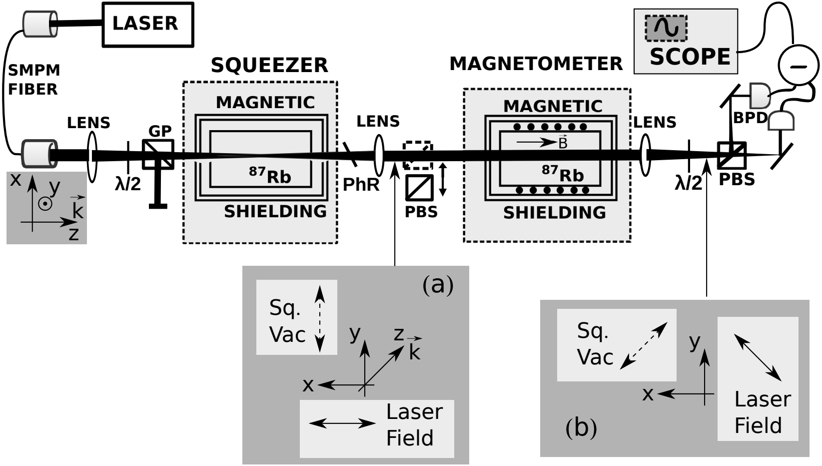


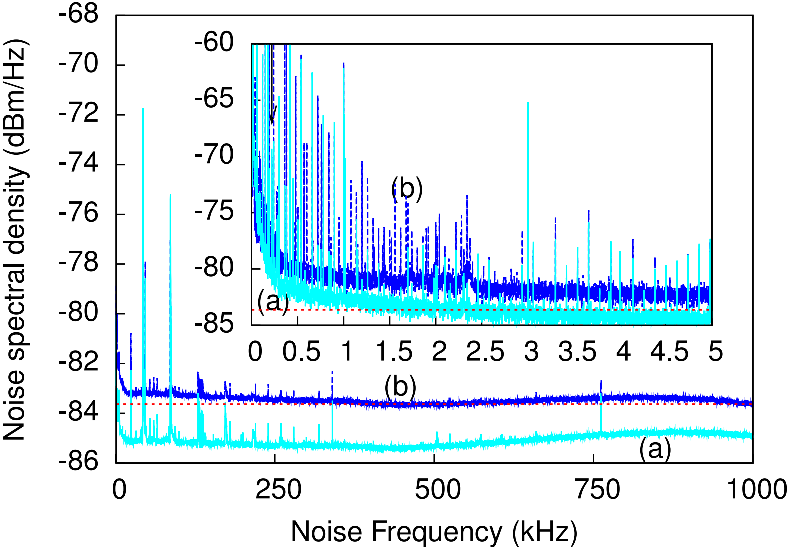

Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

# Squeezed enhanced magnetometer setup

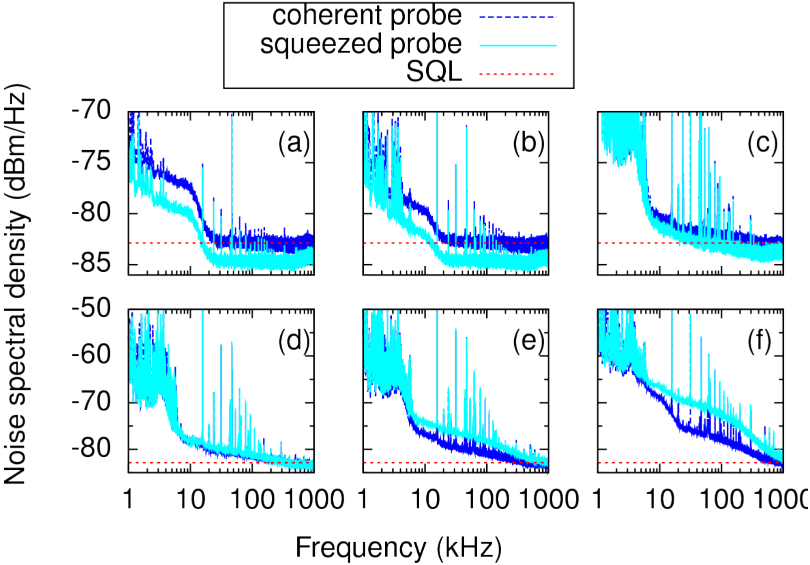



Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

# Magnetometer noise floor improvements

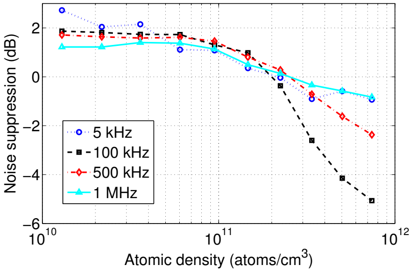


# Magnetometer noise spectra

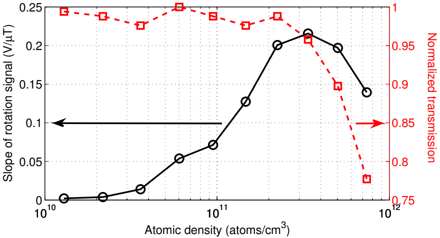


# Noise suppression and response vs atomic density

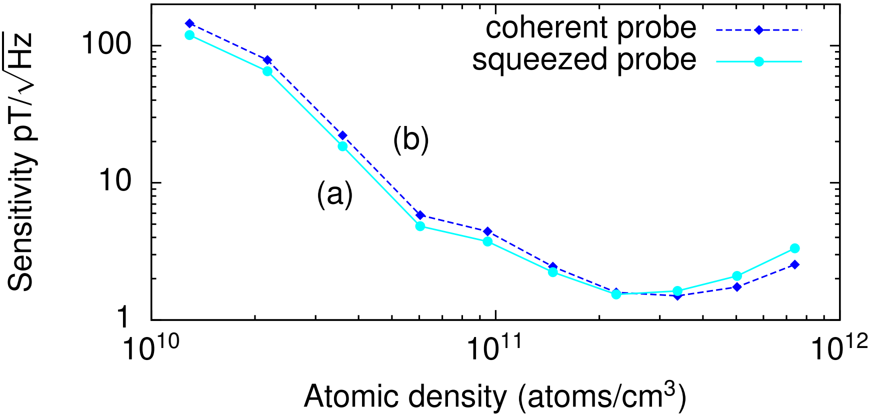
Noise suppression




Response

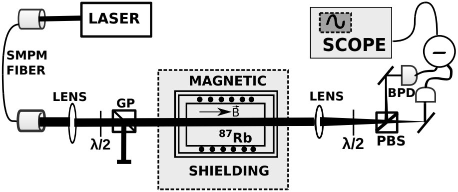


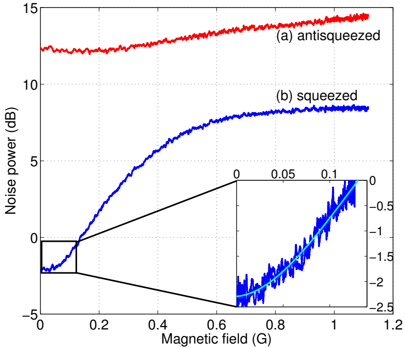
# Magnetometer sensitivity vs atomic density



# Squeezing vs magnetic field

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



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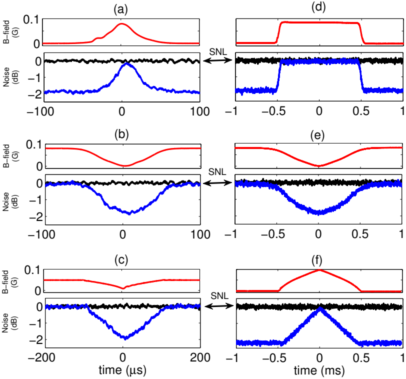
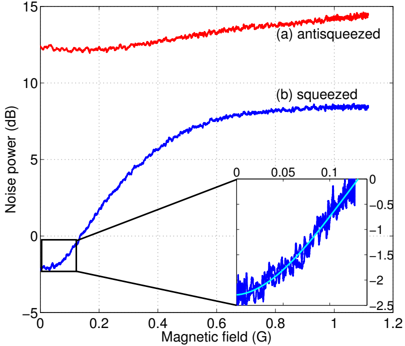
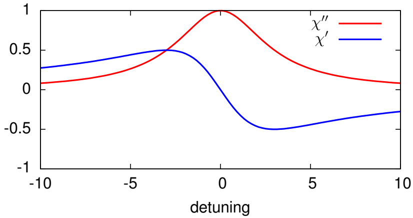


# Light group velocity

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

Susceptibility




Rotation vs B field

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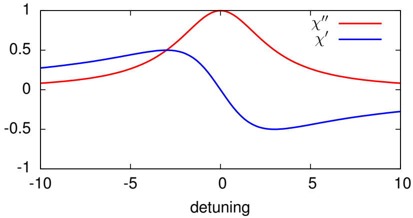
Susceptibility

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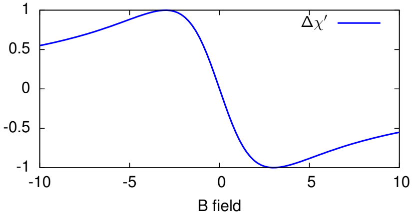

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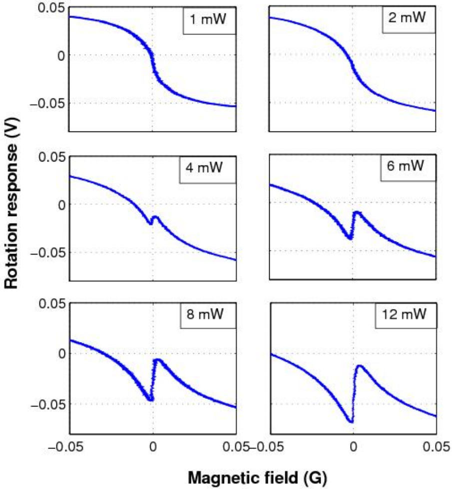
Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

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



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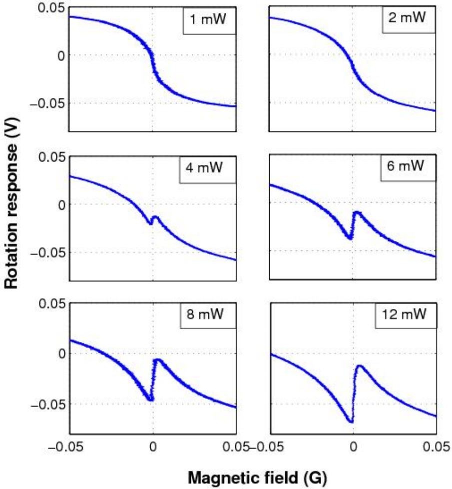
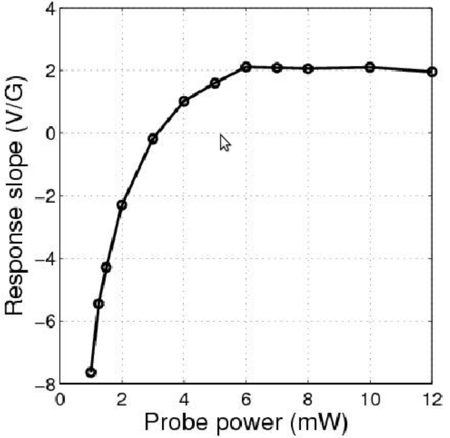
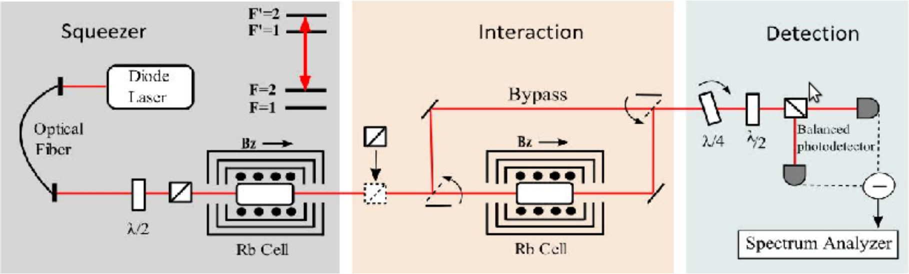
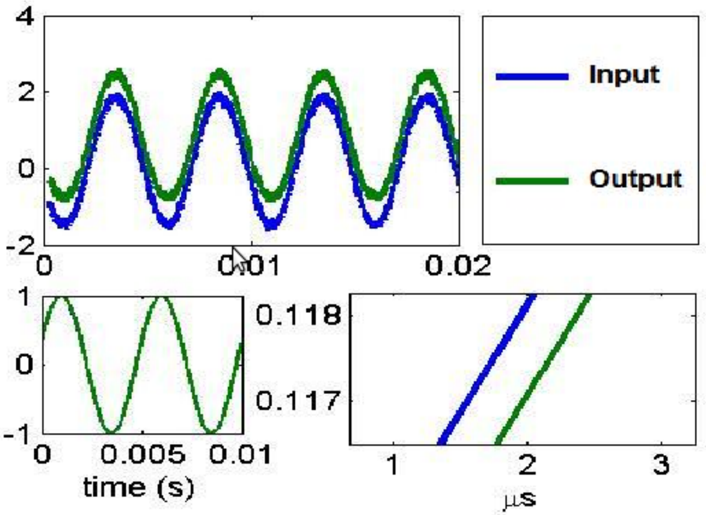


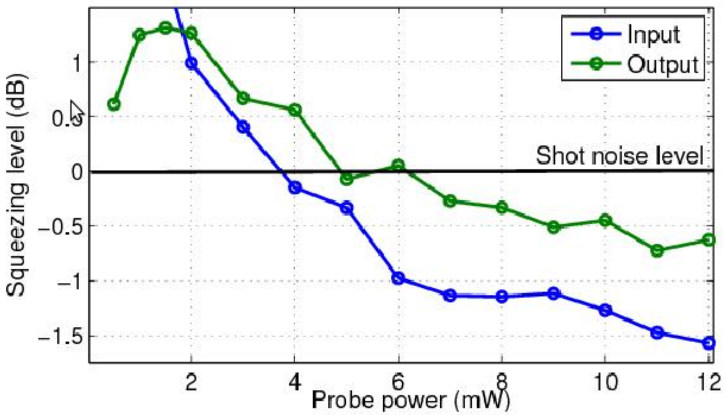
# Time advancement setup



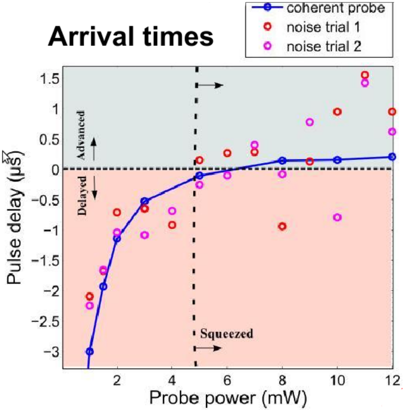
# Squeezing modulation and time advancement



# Squeezing after advancement cell



# Advancement vs power



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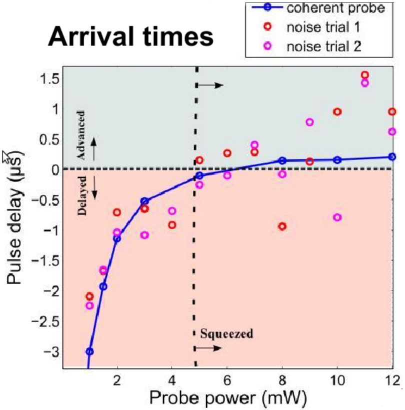


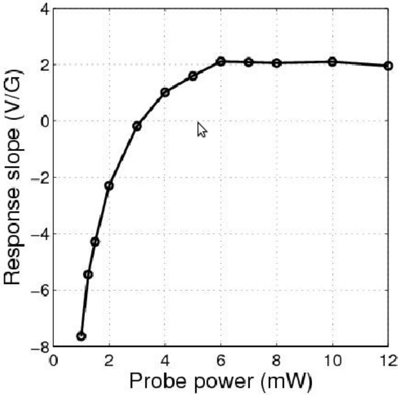

# People

Travis Horrom, W&M

Robinjeet Singh, LSU

Irina Novikova, W&M

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 $\mu$S

For more details:

- Travis Horrom, Robinjeet Singh, Jonathan P. Dowling, Eugeniy E. Mikhailov, “Quantum Enhanced Magnetometer with Low Frequency Squeezing”, **arXiv**:1202.3831, (2012). **PRA** accepted.

Financial support

- Reves Faculty International Conference Travel Grant