SAND2015-3383C

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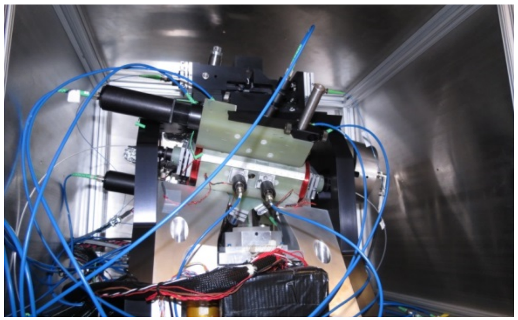

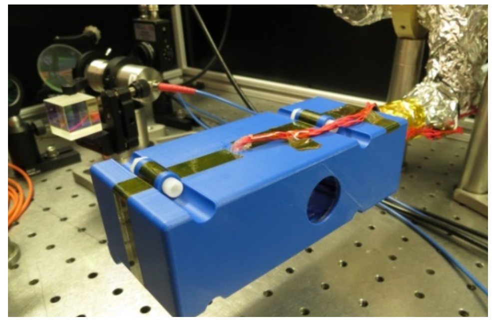

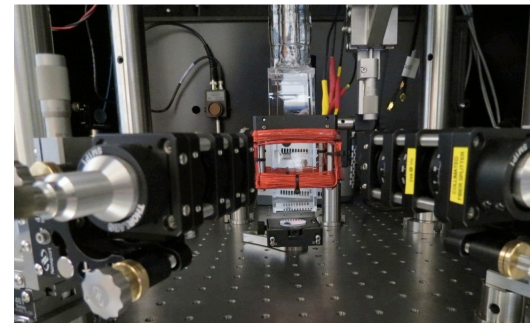

Inertial sensing with atom interferometers

Grant Biedermann

MICRO-TECHNOLOGY DARPA MTO POSITIONING TIMING NAVIGATION

UNM

CQuIC

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). Distribution “A” (Approved for Public Release, Distribution Unlimited)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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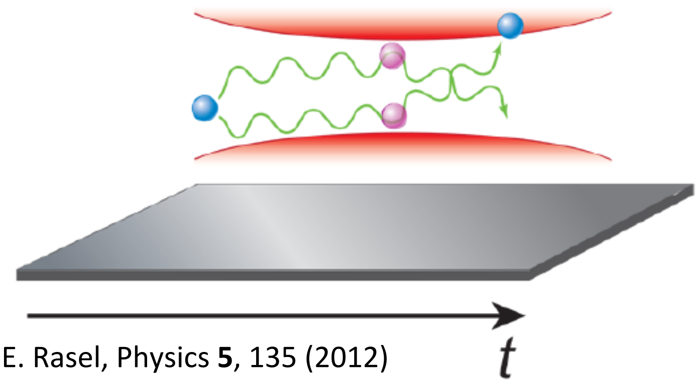
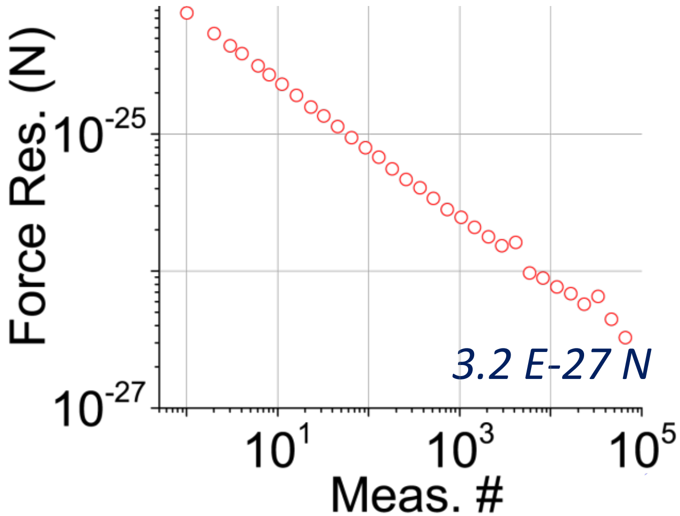
Force resolution of a single atom interferometer

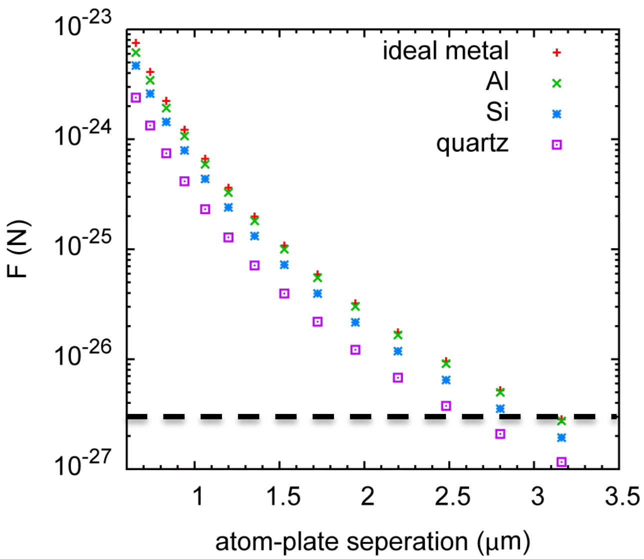


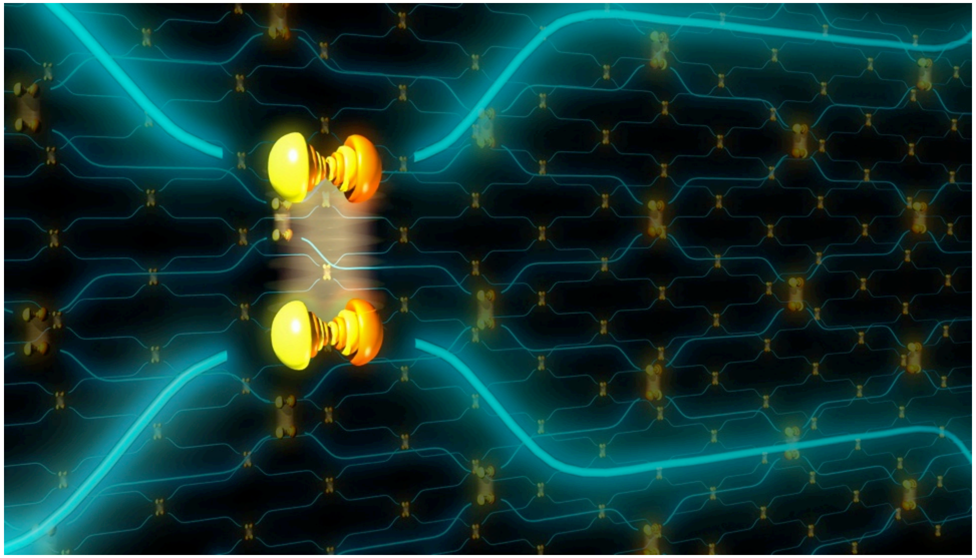
E. Rasel, Physics **5**, 135 (2012)

Parazzoli, et al., Phys. Rev. Lett. **109**, 230401 (2012)



Casimir-Polder force





* For cesium 3.2 E-27 N is 1.5 m*g*

Demonstrated entanglement, arXiv:1501.03862

Light-pulse atom interferometry

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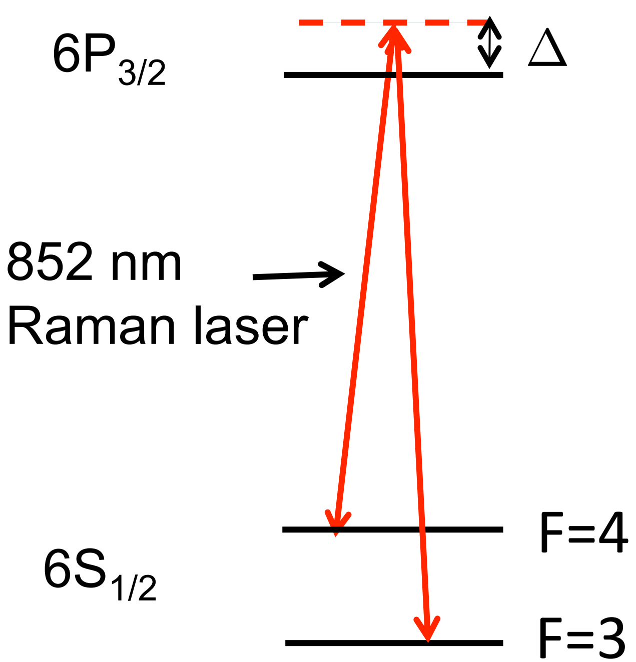
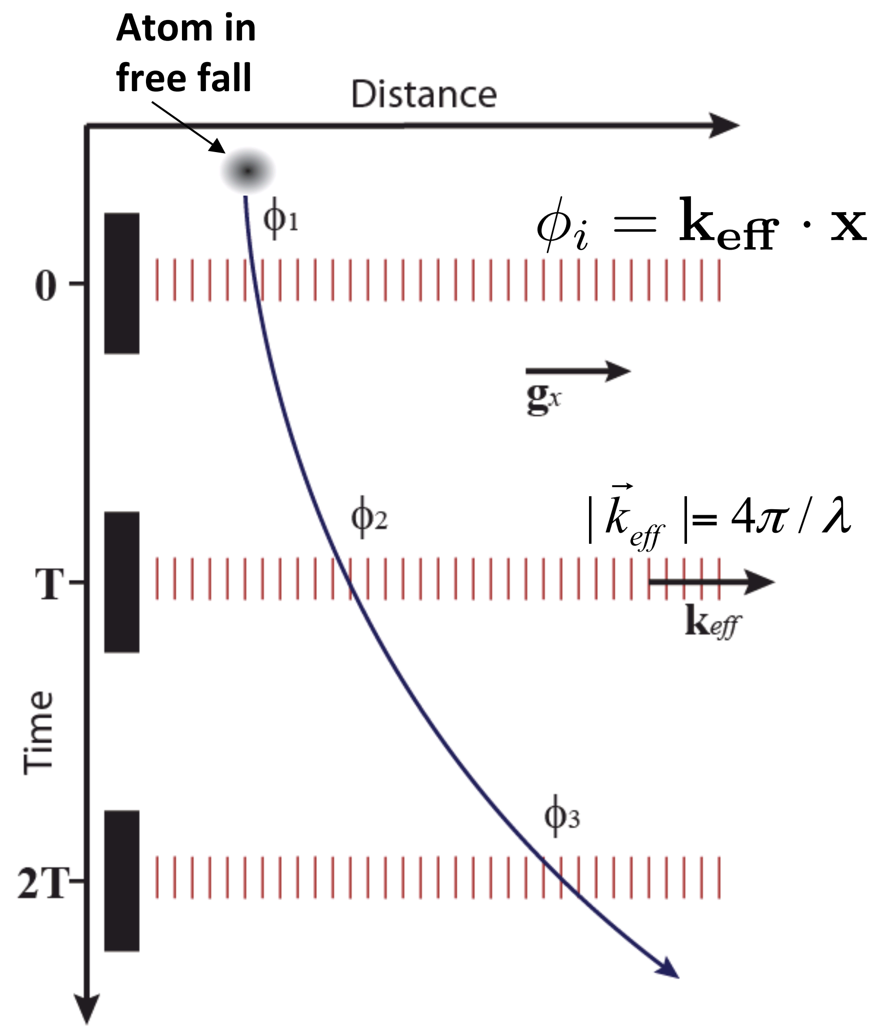


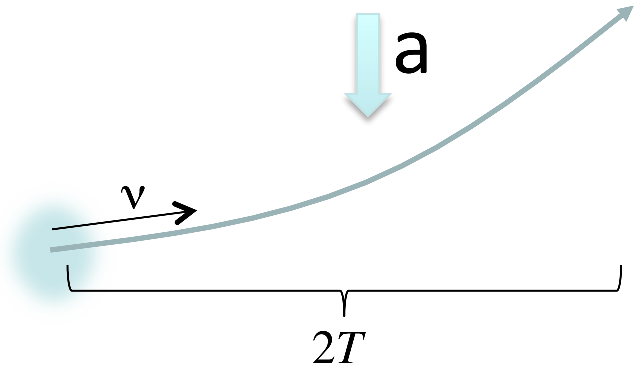
stimulated Raman transition

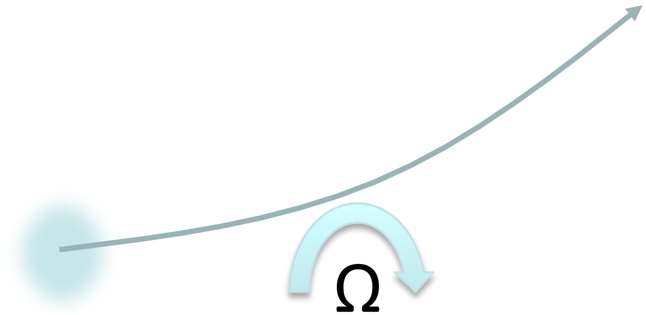


For an atom starting in F=3: $P_{F=4} = \frac{1}{2}(\cos\Delta\phi)$ & $\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$

Measuring acceleration and rotation with a particle in free-fall

1-particle

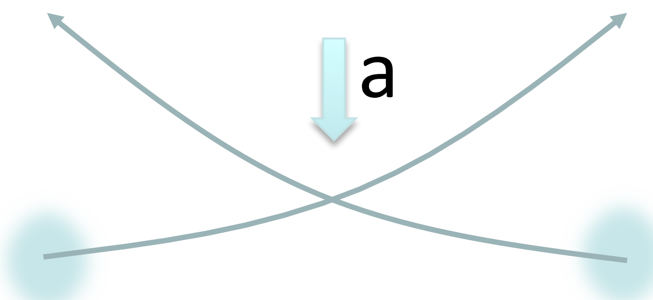


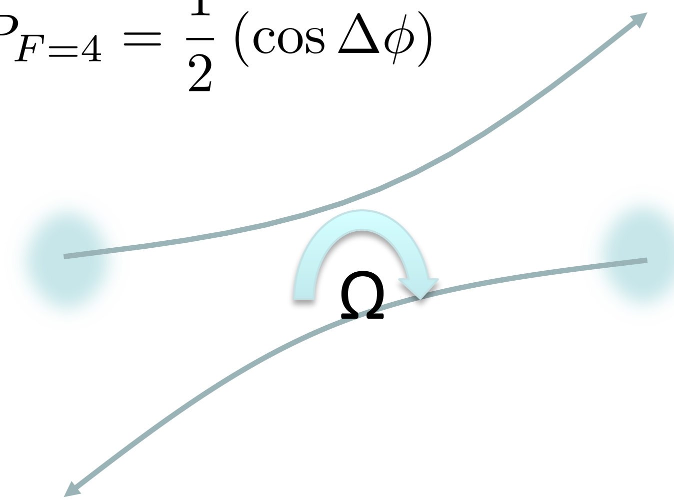


Interferometer phase shift: $\Delta\phi = \vec{k}_{eff} \cdot \left(\vec{a}T^2 - 2(\vec{v} \times \vec{\Omega})T^2\right)$

$$P_{F=4} = \frac{1}{2}(\cos\Delta\phi)$$

2-particles





Sensitivity increases with T^2

Launch and recapture

Steady state atom number:

$$N_s = \frac{\alpha \eta T_c}{\beta T_c + (1 - r_0)}.$$

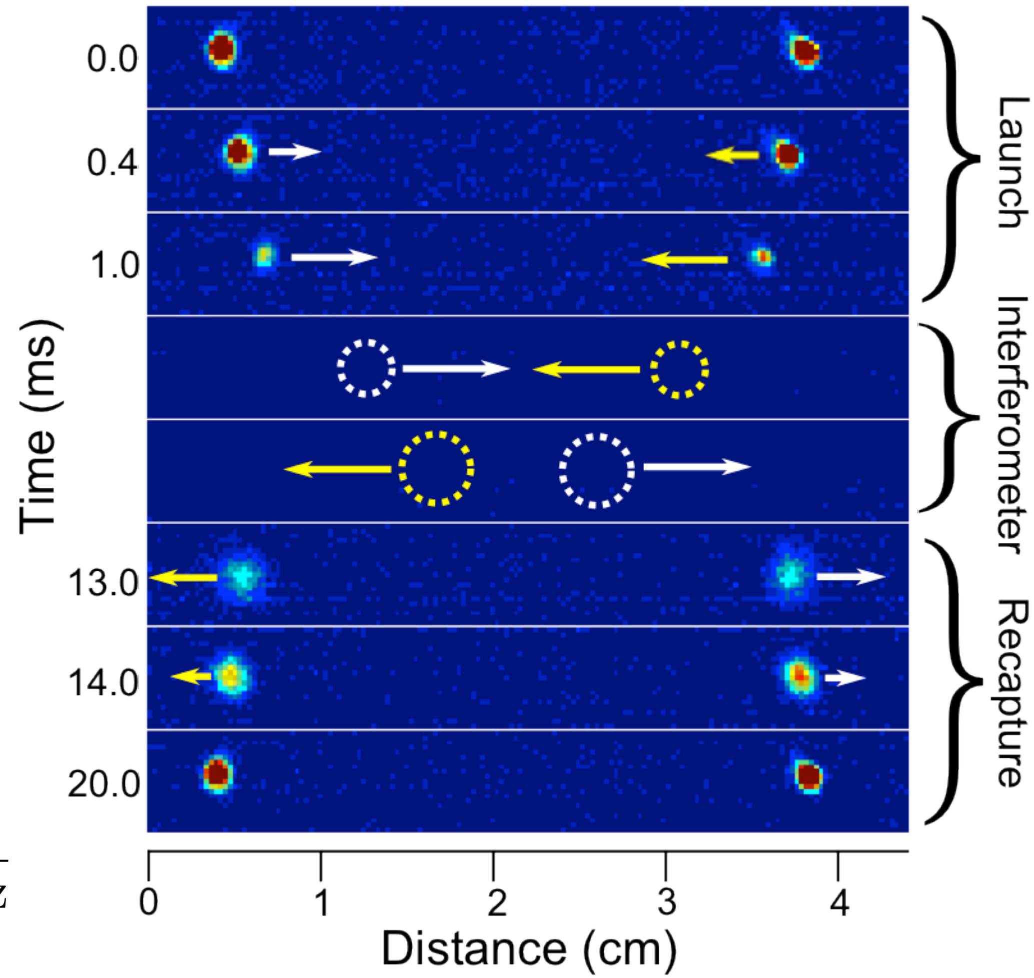
Base recapture efficiency r_0 = 96 %

Benefits

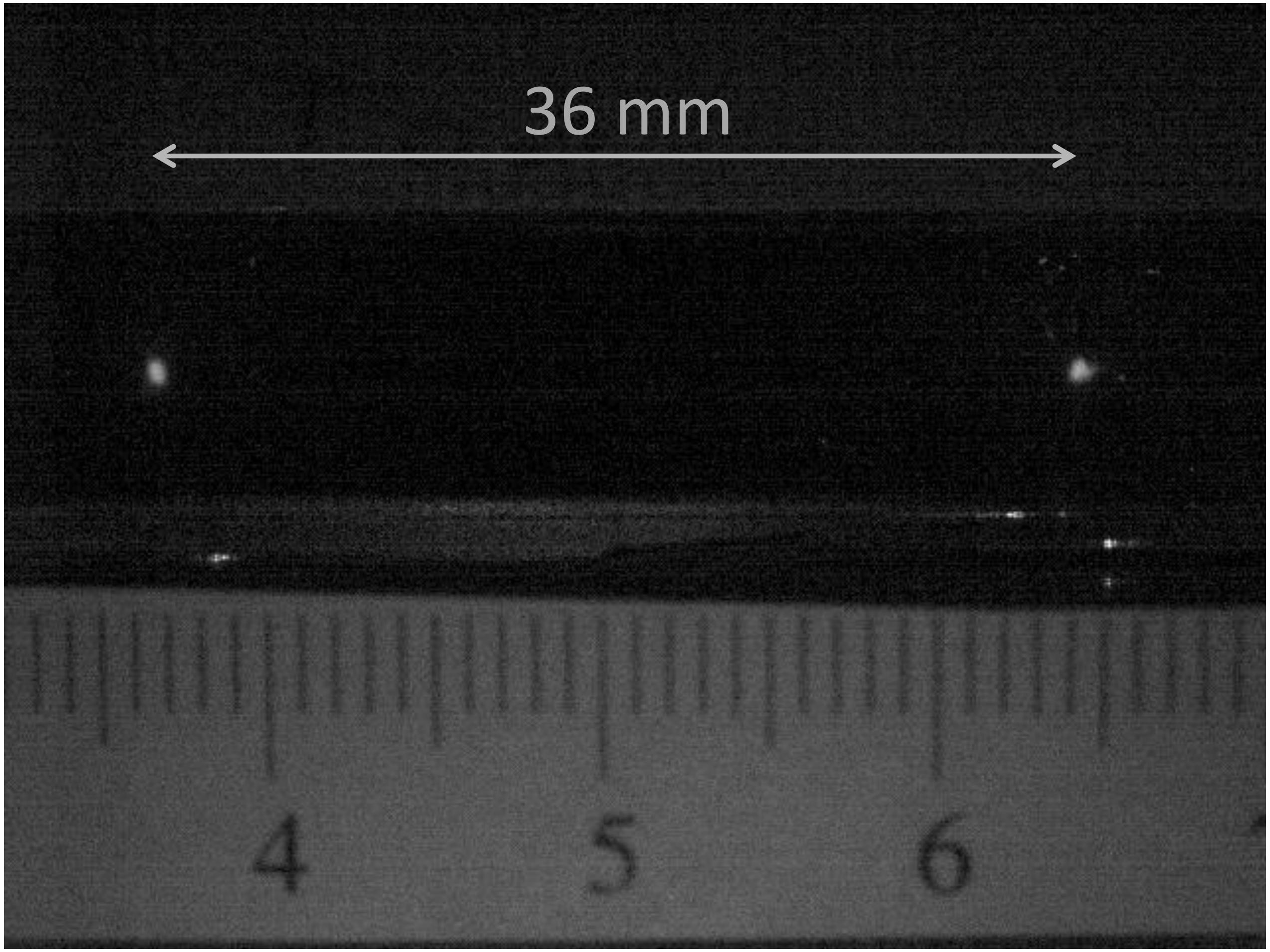
- Increases signal by 10x
- Data rates > 50 Hz
- Minimizes cycle dead time
- Reduced complexity
- Sufficient for:

$33\ \mathrm{n}g/\sqrt{\mathrm{Hz}}$ & $70\ \mathrm{nrad/s}/\sqrt{\mathrm{Hz}}$

CCD images of ensemble exchange



Launch and recapture



- Repeats at ≈ 60 measurements per second

Experiment platform

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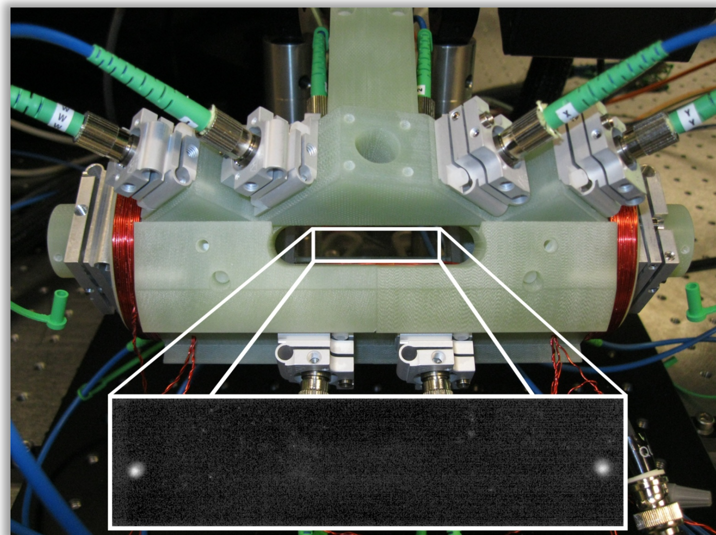
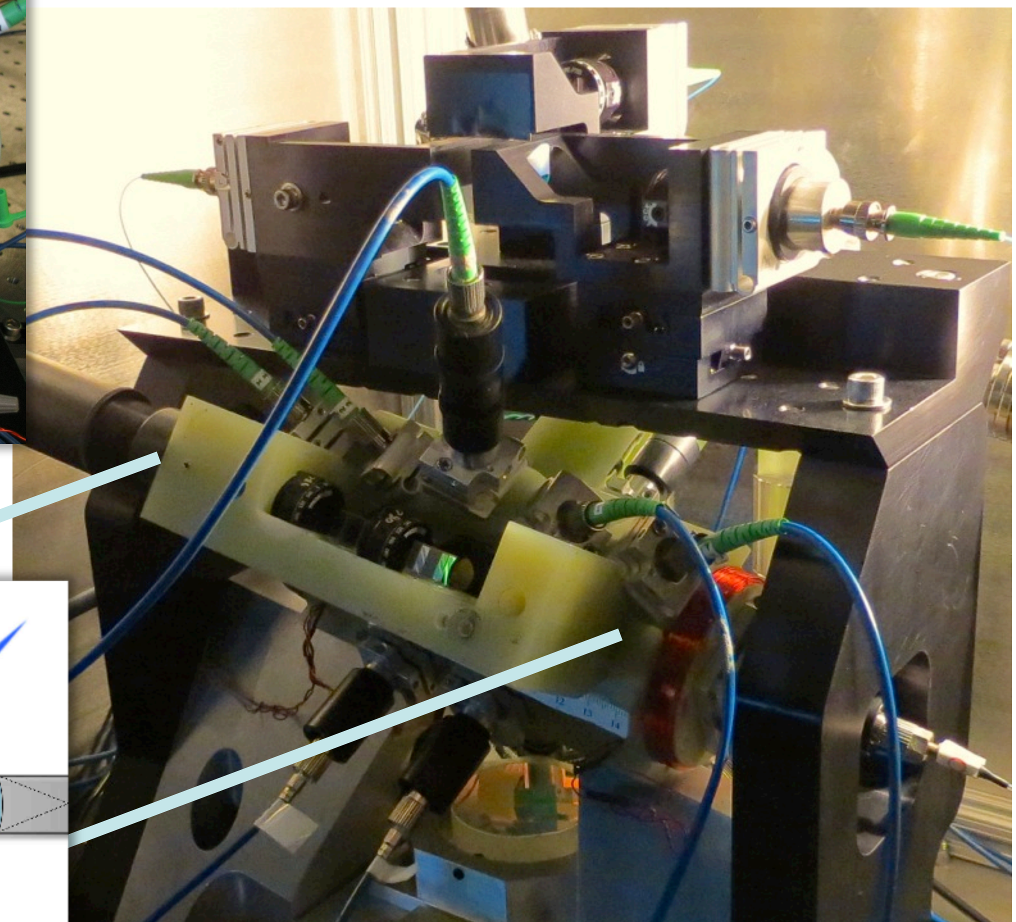
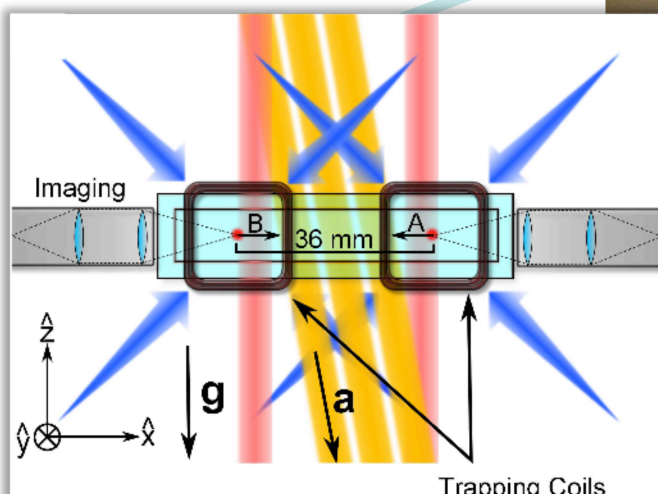


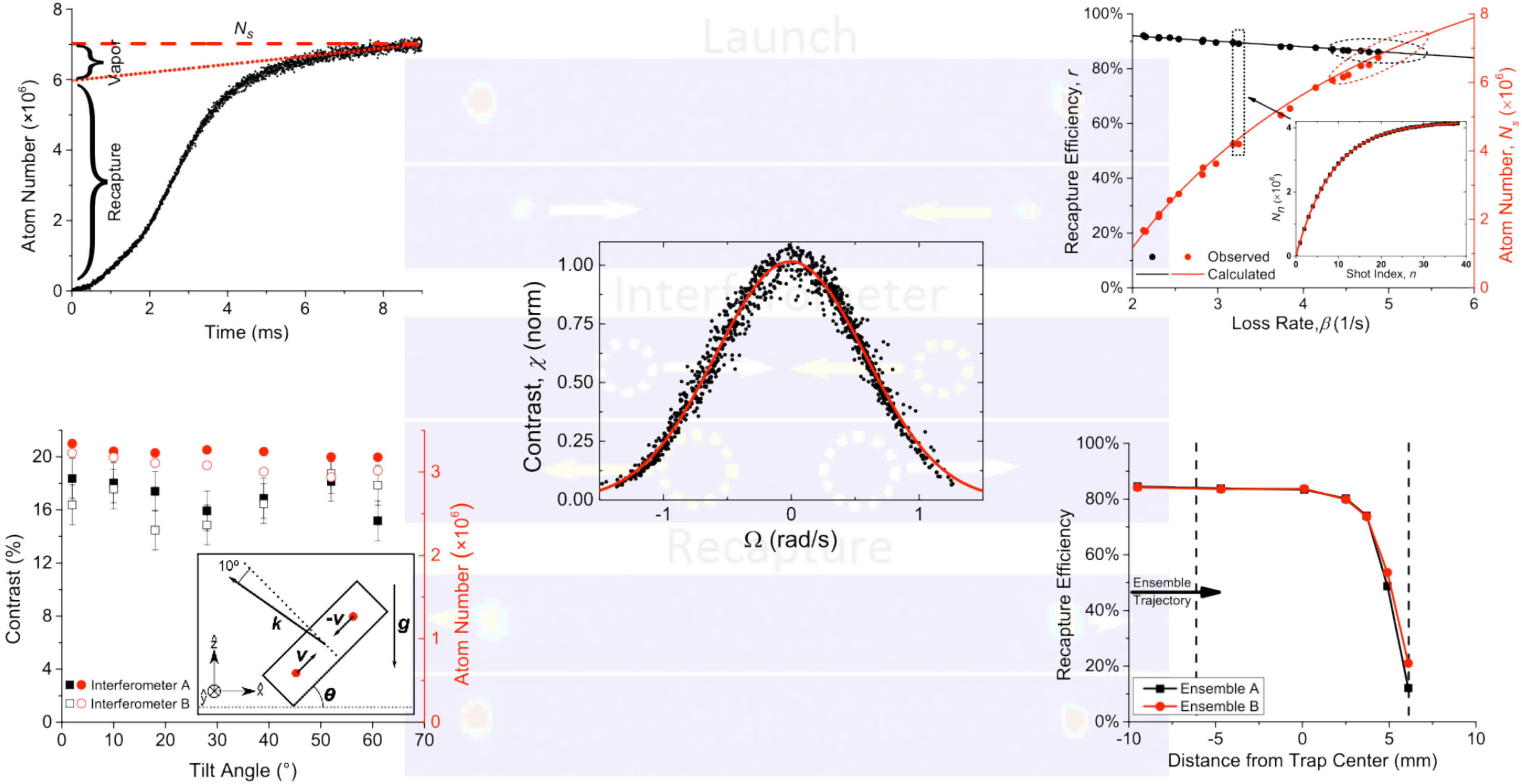
Picture of interferometer sensor





Characterizing ensemble exchange

- Dynamic aspects of Ensemble Exchange characterized
- Robust to rotations, tilts and displacements



Angular acceleration and jerks

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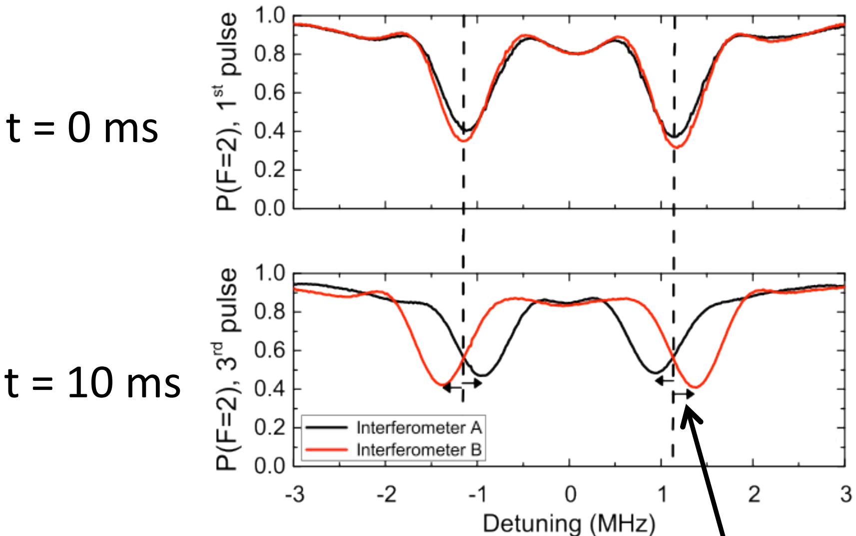
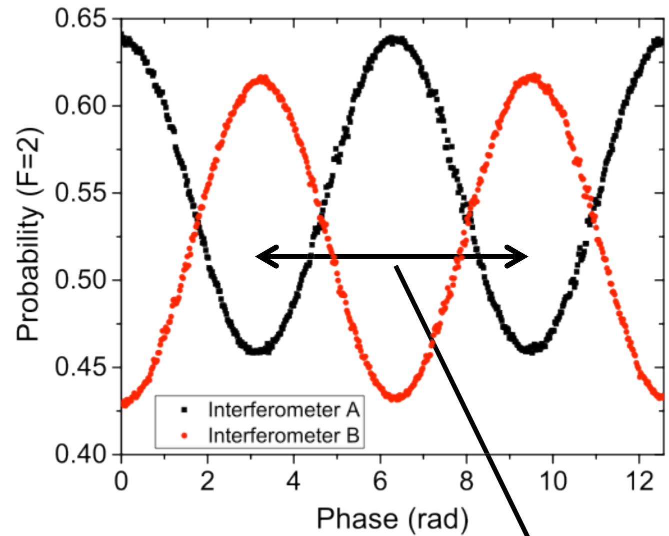
Controlling frequency and phase in a dynamic environment

Raman laser frequency scan



Significant detuning develops over 10 ms due to gravitationally-driven Doppler shift

Raman laser phase scan

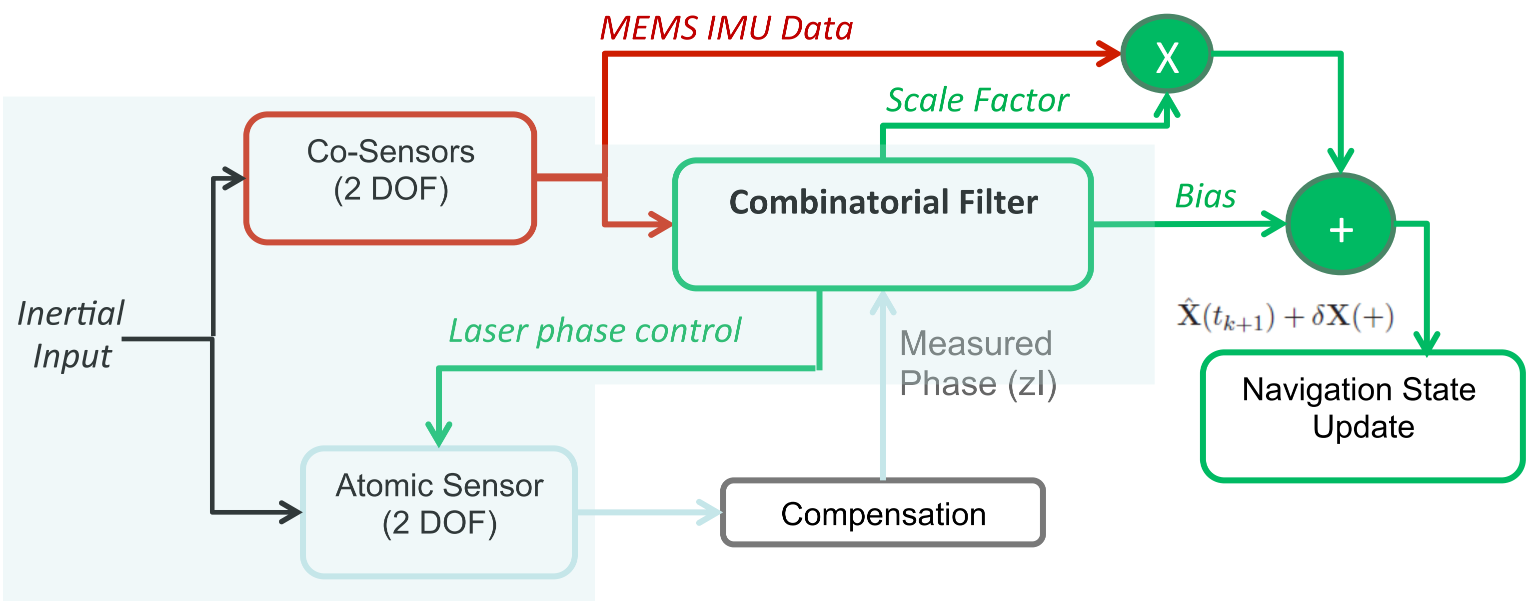


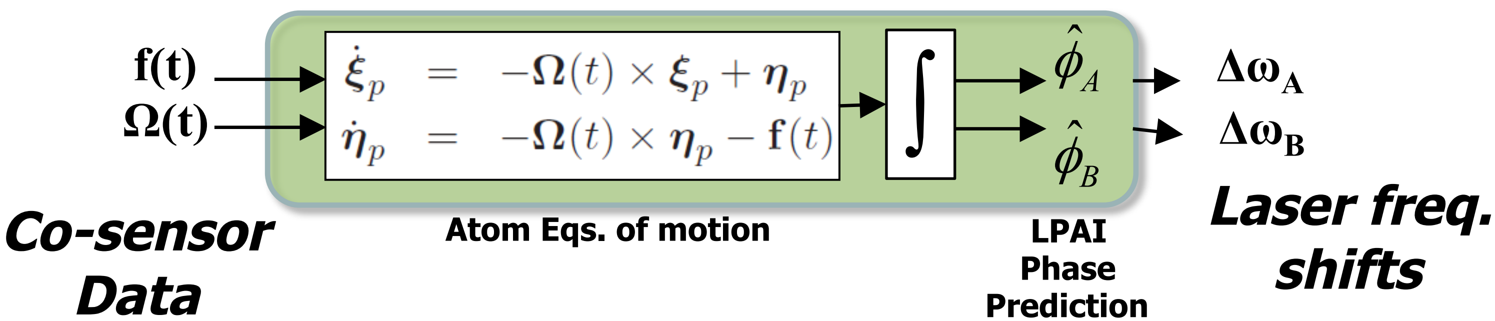
≈ m*g* OR ≈ mrad/s (400 deg/hr)

Small changes in acceleration or rotation during one interferometer cycle cause phase slip

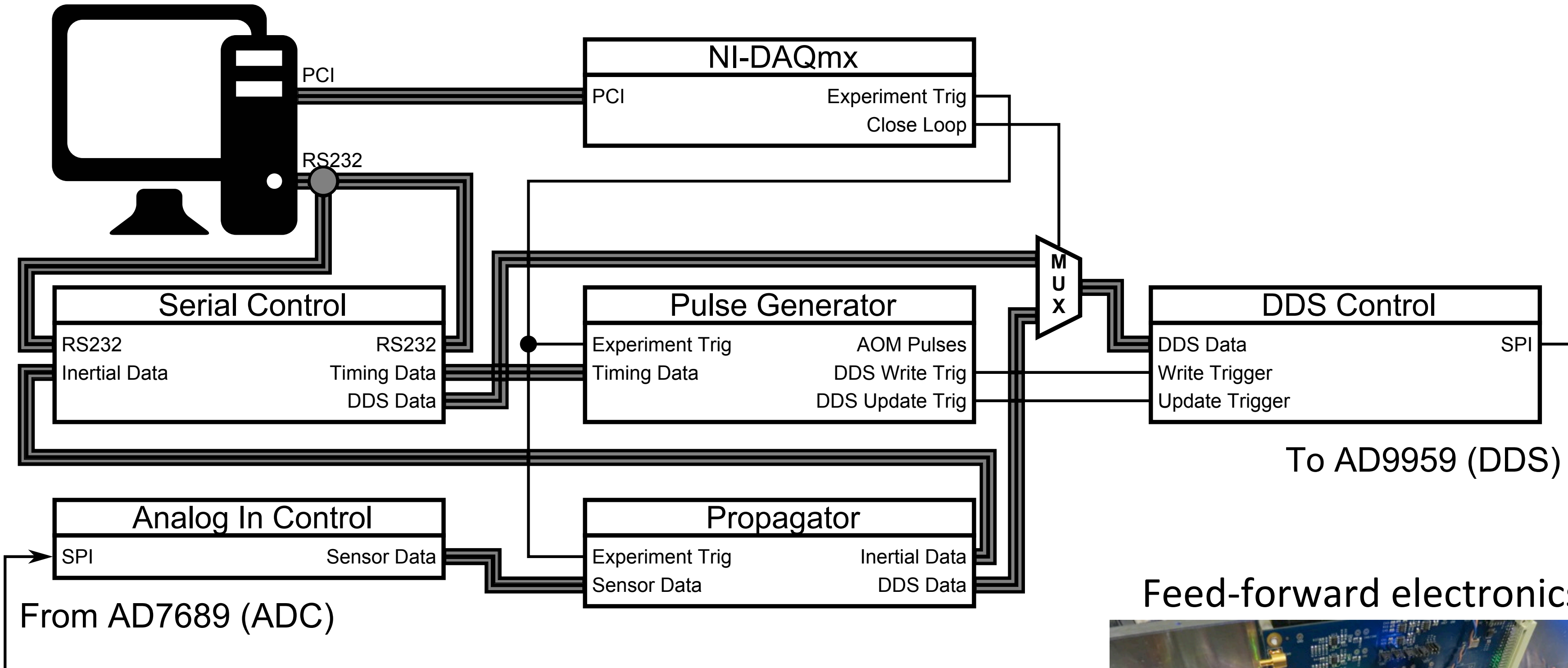
Technical challenge

- Real-time cosensor read, Runge-Kutta propagator calculation, and phase/frequency write to interferometer laser in less than 0.5 ms (note: T = 4.5 ms)

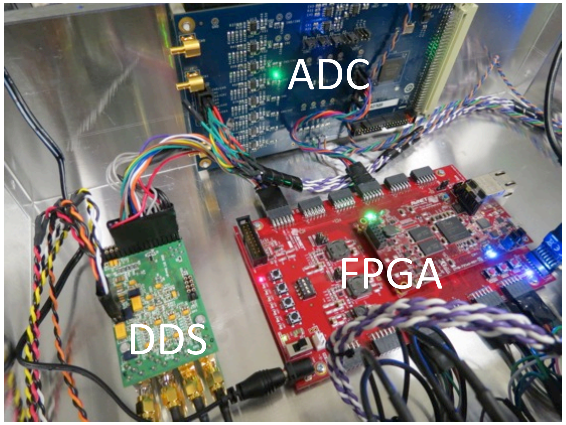




Control hardware



Feed-forward electronics

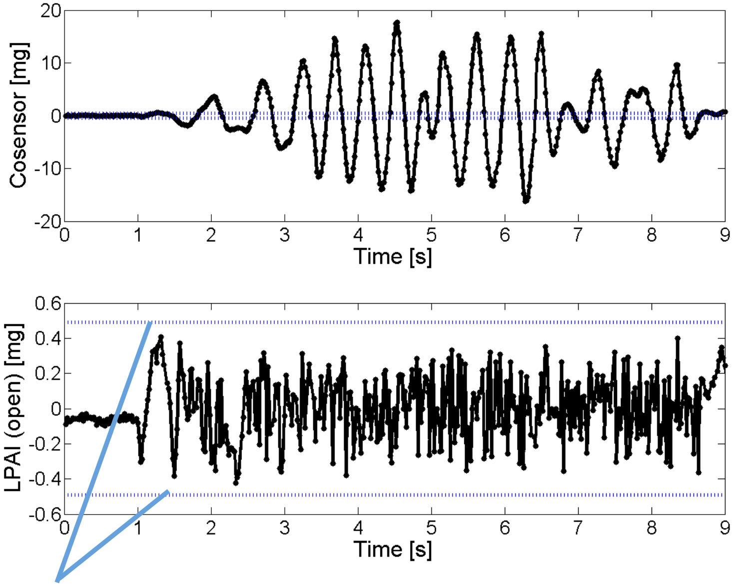


Phase feed-forward results

OPEN LOOP

Cosensor accel.

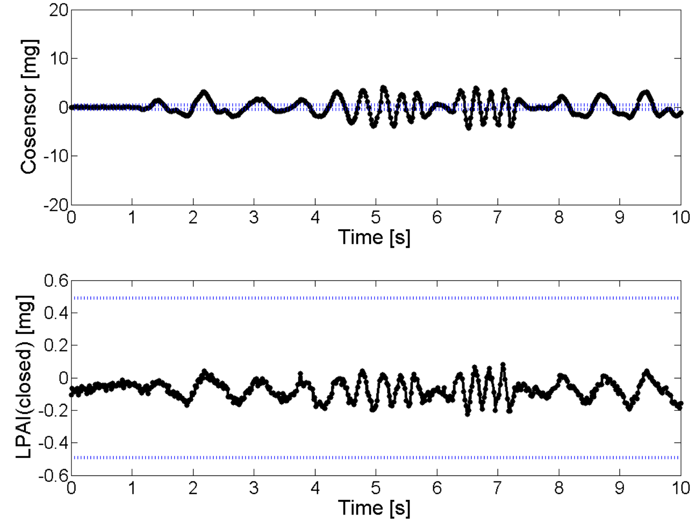
LPAI accel.



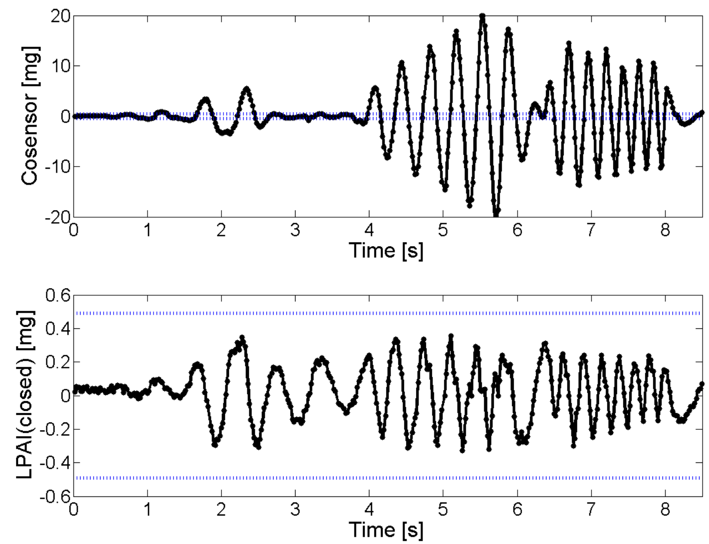
LPAI $\pi/2$ limits

FEED FORWARD

Small amplitude



Large amplitude

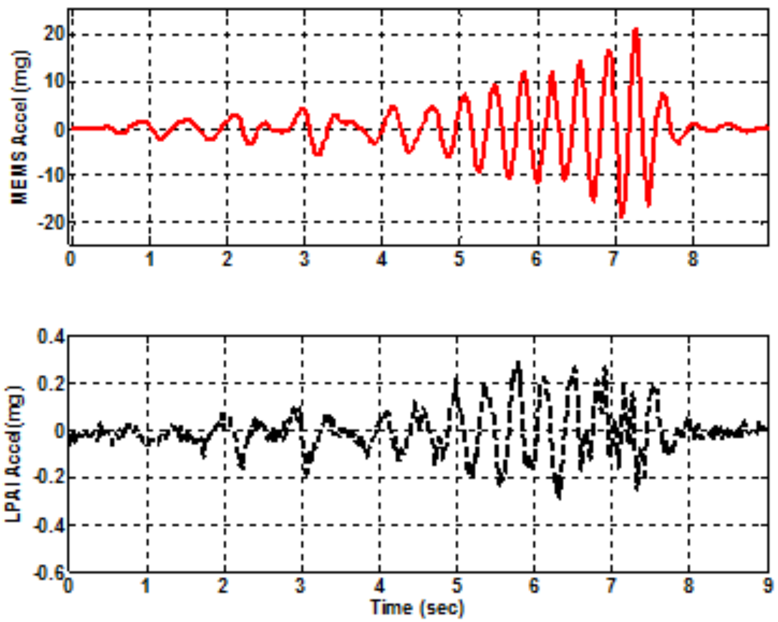


<u>Initial results:</u>

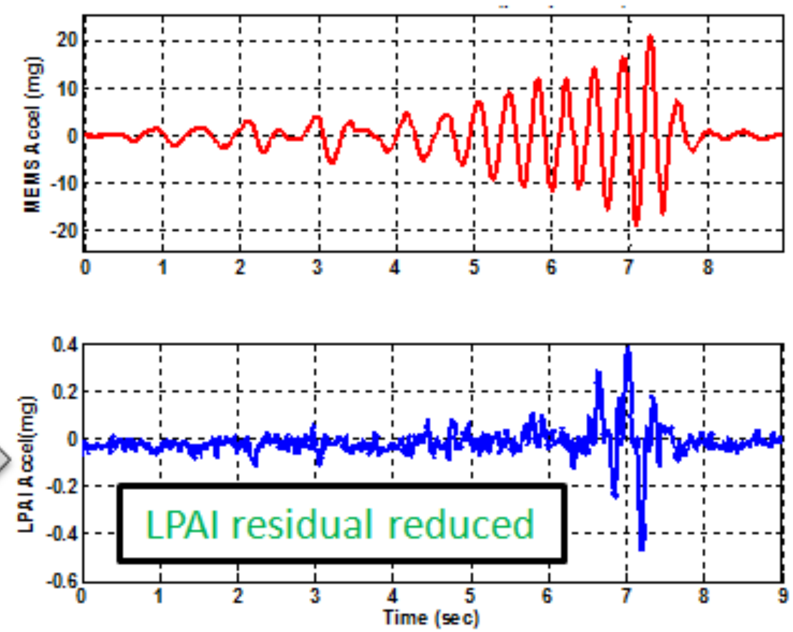
- Accelerometer only
- Feed forward successfully locks LPAI phase to within π radians
- Extends dynamic range to ≈ +/- 10 mg

Phase feed-forward results

LPAI feedback would increase dynamic range >10x



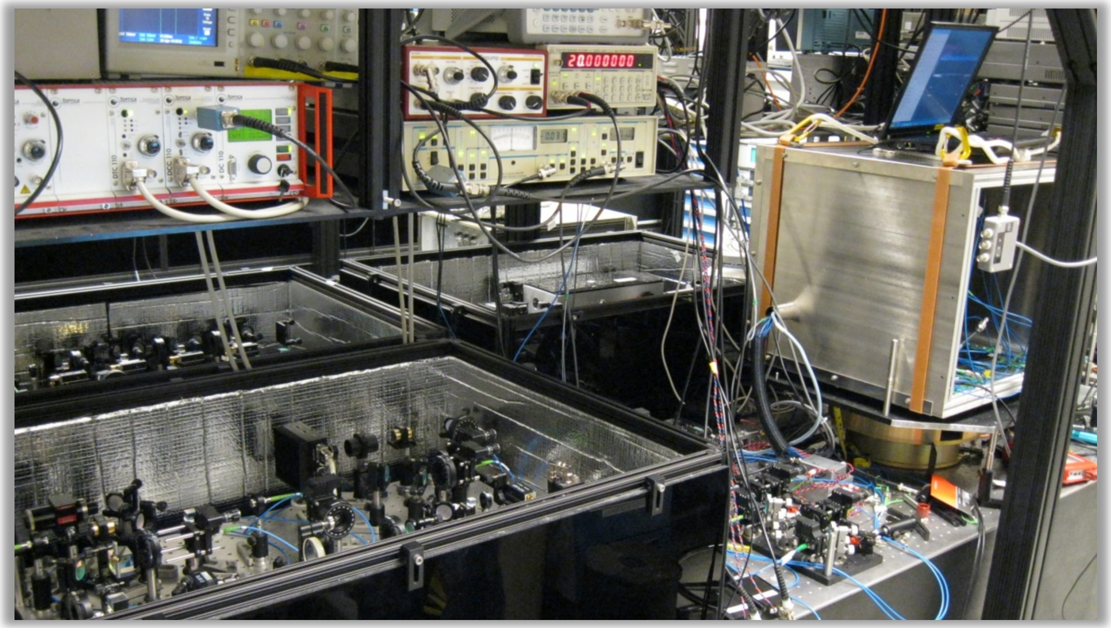
MEMS accel scale factor corrected (post-process)



Initial results:

- Accelerometer only
- Feed forward successfully locks LPAI phase to within π radians
- Extends dynamic range to ≈ +/- 10 *mg*

Exploring ultra-short T



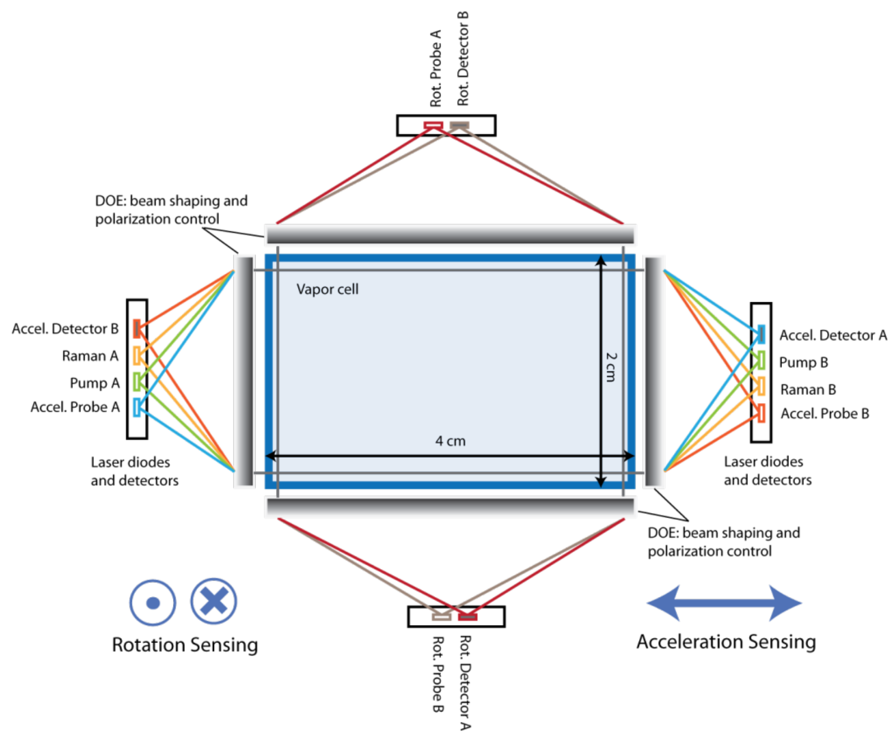
Sandia atom interferometer
- Laser cooled ensemble
- >1,000,000 cc

- Want a small, low-power, low-cost atomic accelerometer
- Warm vapor approach has historically made excellent gyros, clocks and magnetometers.
- What about accelerometers?

Symmetricom SA.45s CSAC
- Warm vapor ensemble
- 17 cc

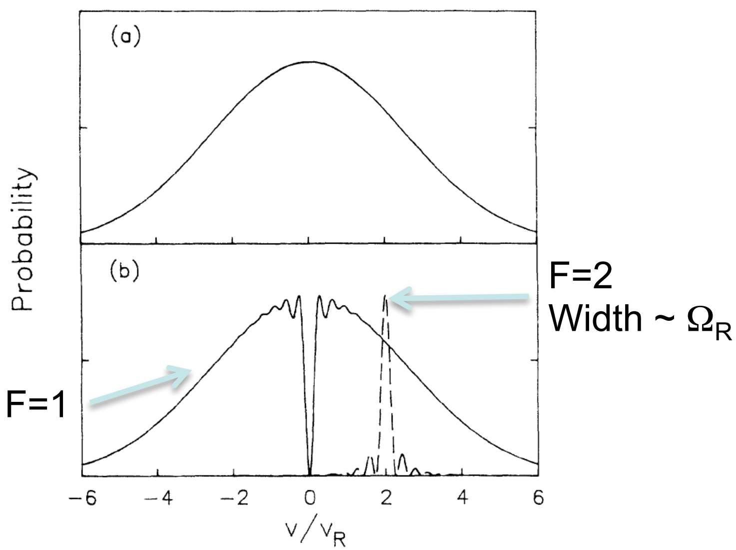
Warm vapor concept

- Using the Doppler sensitivity of Raman transitions, and ultra-short duration atom interferometry, LPAI is possible in a warm vapor
- The challenge: Target atom shot noise limit on 10^8 atoms



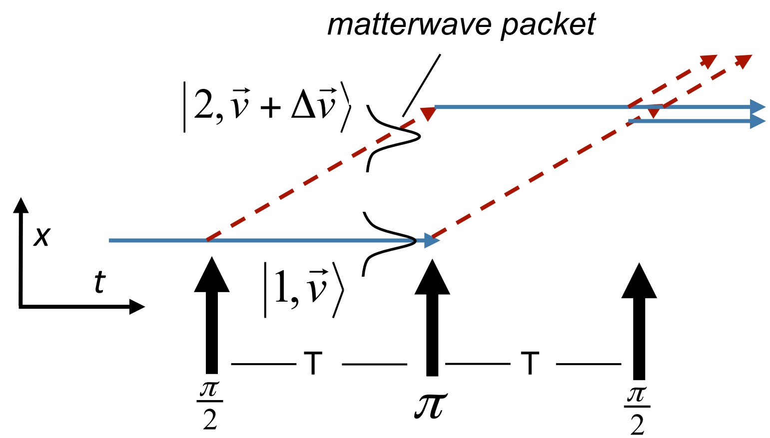
Motivation: potentially highly compact and simplified. Conceptual diagram (not to scale) of a 2-axis atomic sensor.

Velocity selectivity of Raman pulse



Result of Raman transition used for LPAI

K. Moler, et al., *Phys. Rev. A*, 45, 342 (1992)



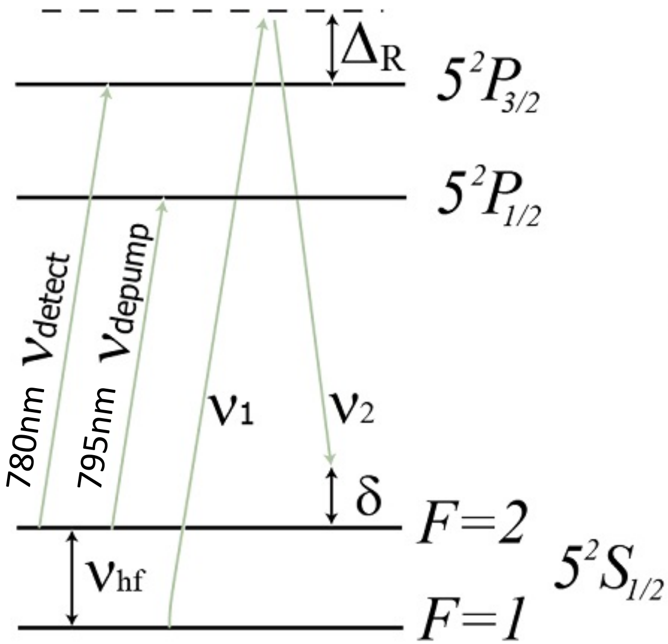
Analyze in momentum space

- each atom interferes with itself
- Non-ideal paths do not contribute to fringe

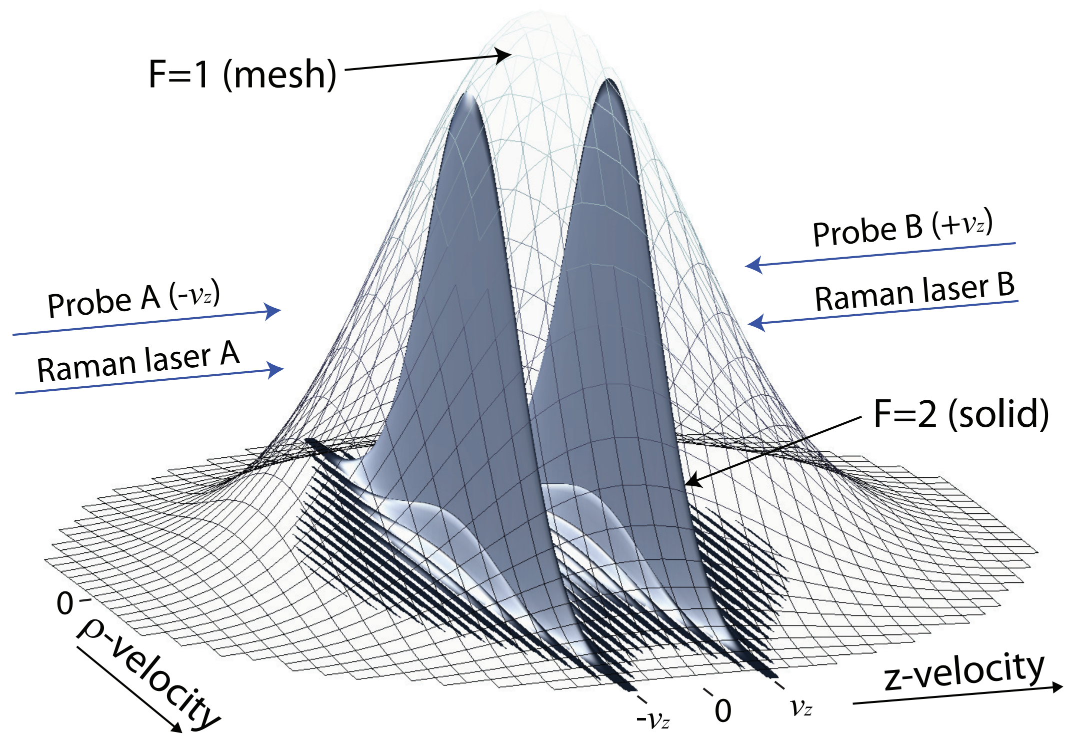
$$\Delta\phi = \mathbf{k}_{\text{eff}} \cdot (\mathbf{g} - \mathbf{2v} \times \mathbf{\Omega})\mathbf{T^2}$$

Warm vapor atom interferometer

Ultra-short T



Simplified laser frequency requirements: potential for miniaturization



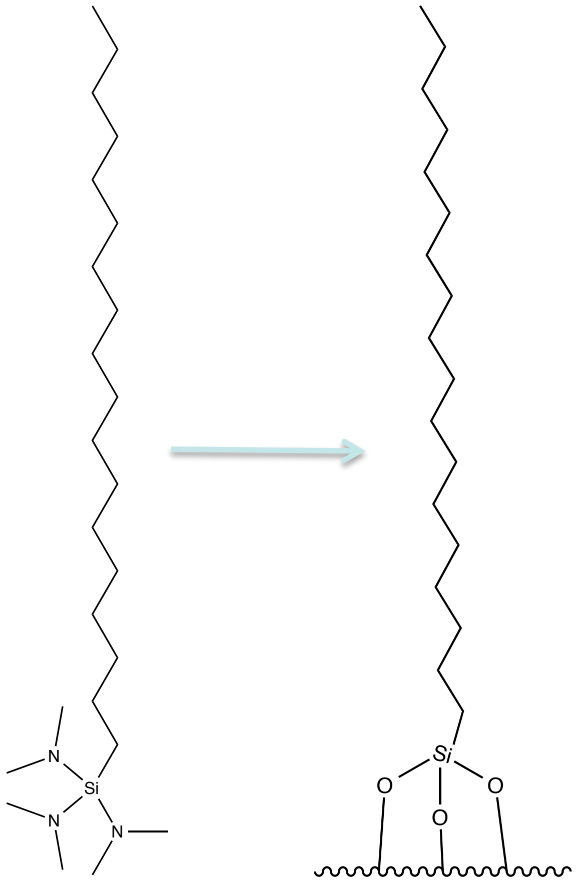
State preparation

To eliminate background signal, must depump all velocity classes

In-house coating development

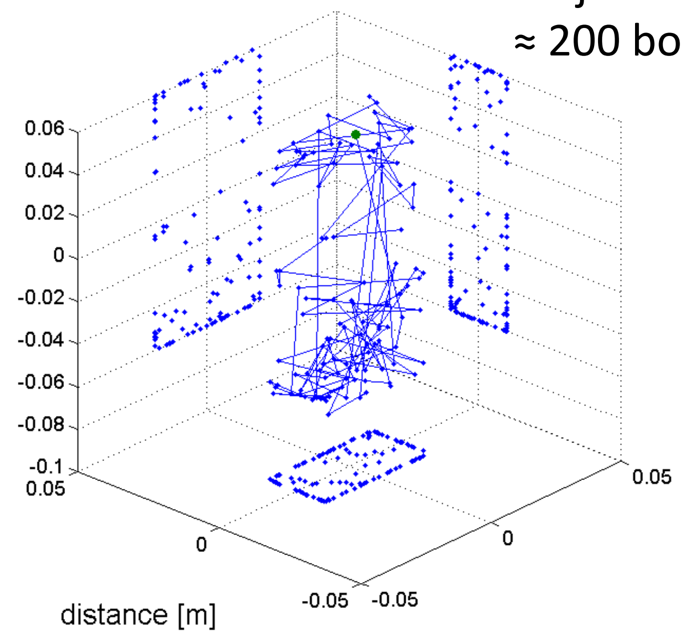
Tris(N,N-dimethylamino)octadecylsilane

measured: τ = 23 ms hyperfine state lifetime



Idealized Bonding

Trajectory simulation
≈ 200 bounces



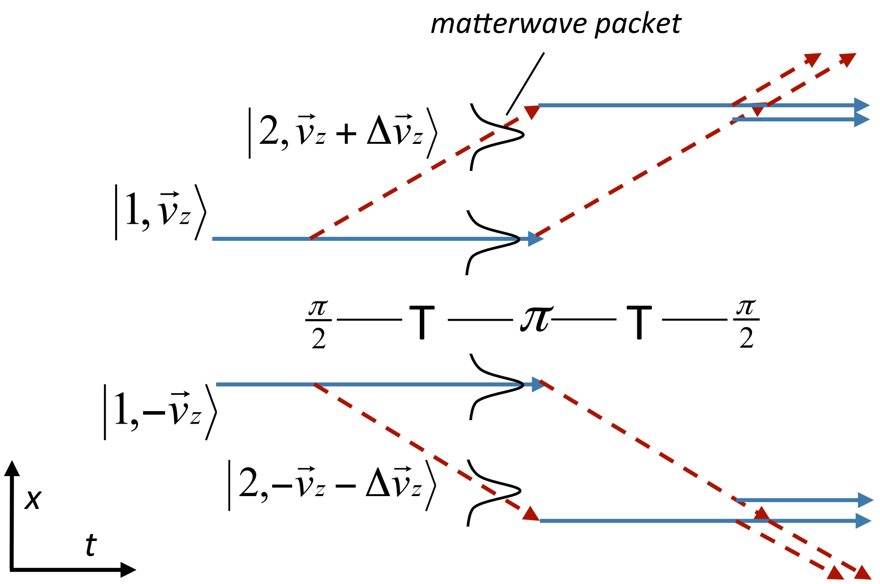
Must be inertially pure—no collisions!
Coating outgassing < 10^{-4} Torr
No buffer gas

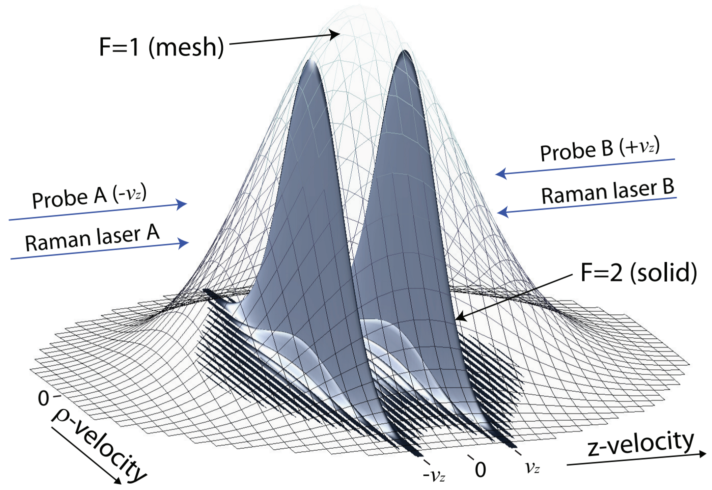
Simultaneous interferometers

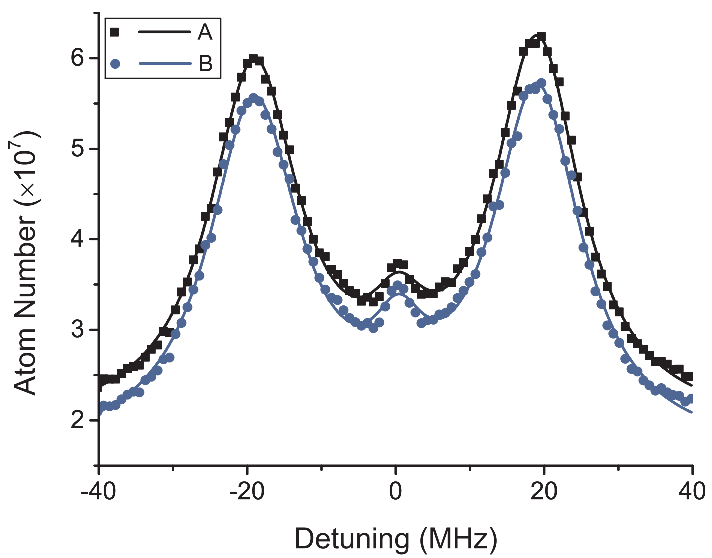
Common mode noise rejection

$$\Delta\Phi = \mathbf{k} \bullet \mathbf{a}\, T^2$$

Simultaneous interferometers







Simultaneous interferometers

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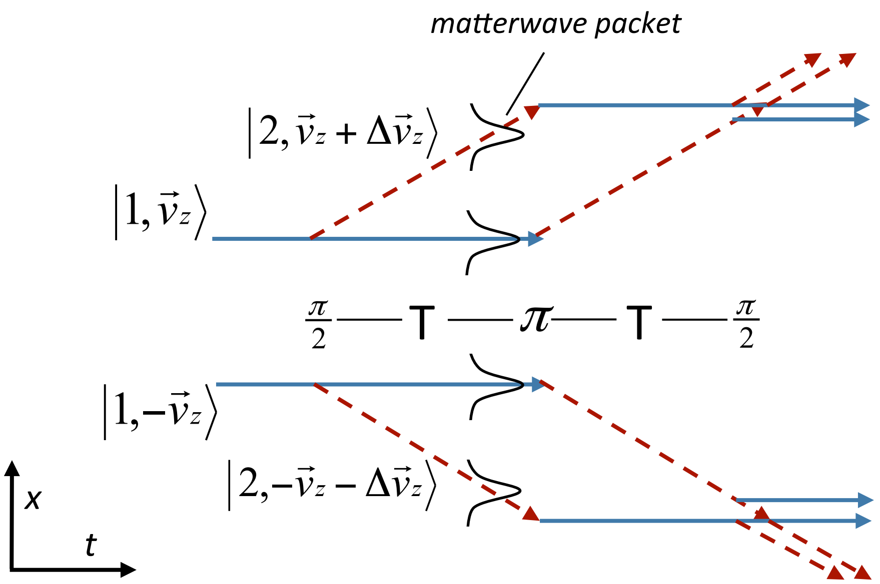
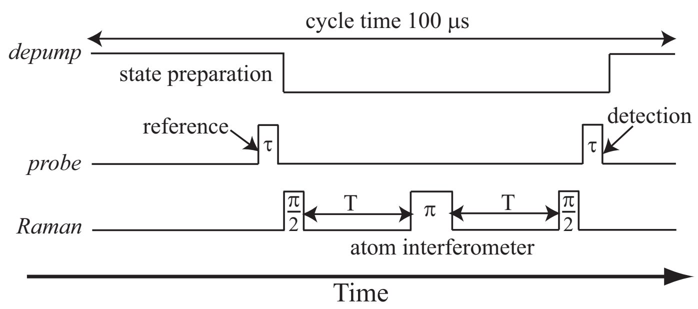
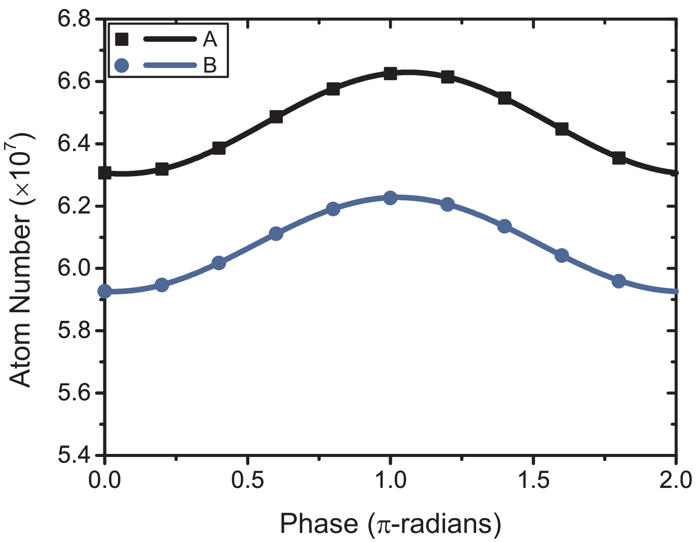
Simultaneous interferometers

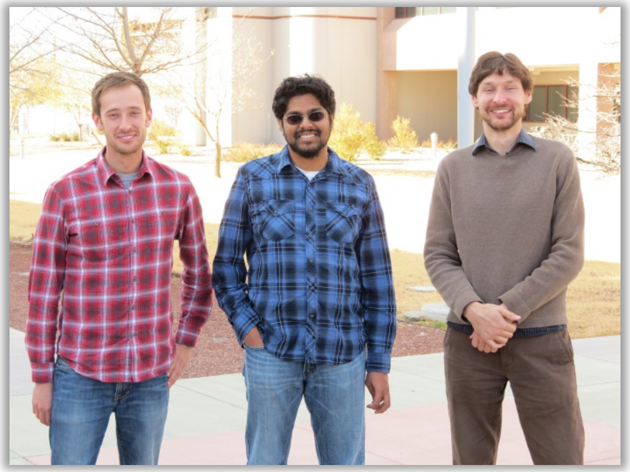






Measured:

- without CMR: 40 mg/√Hz
- With CMR: 10.4 mg/√Hz


G. Biedermann, A. Rakholia, H. McGuinness

Not pictured

- Yuan-Yu Jau
- David Wheeler
- David Johnson
- David Butts