SAND2015-4860PE

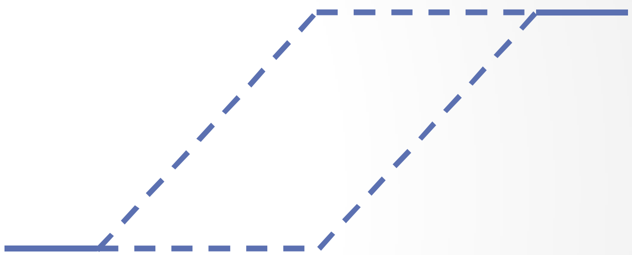
High Data-Rate Atom Interferometry for Dynamic Acceleration and Rotation

Akash Rakholia

June 15th, 2015

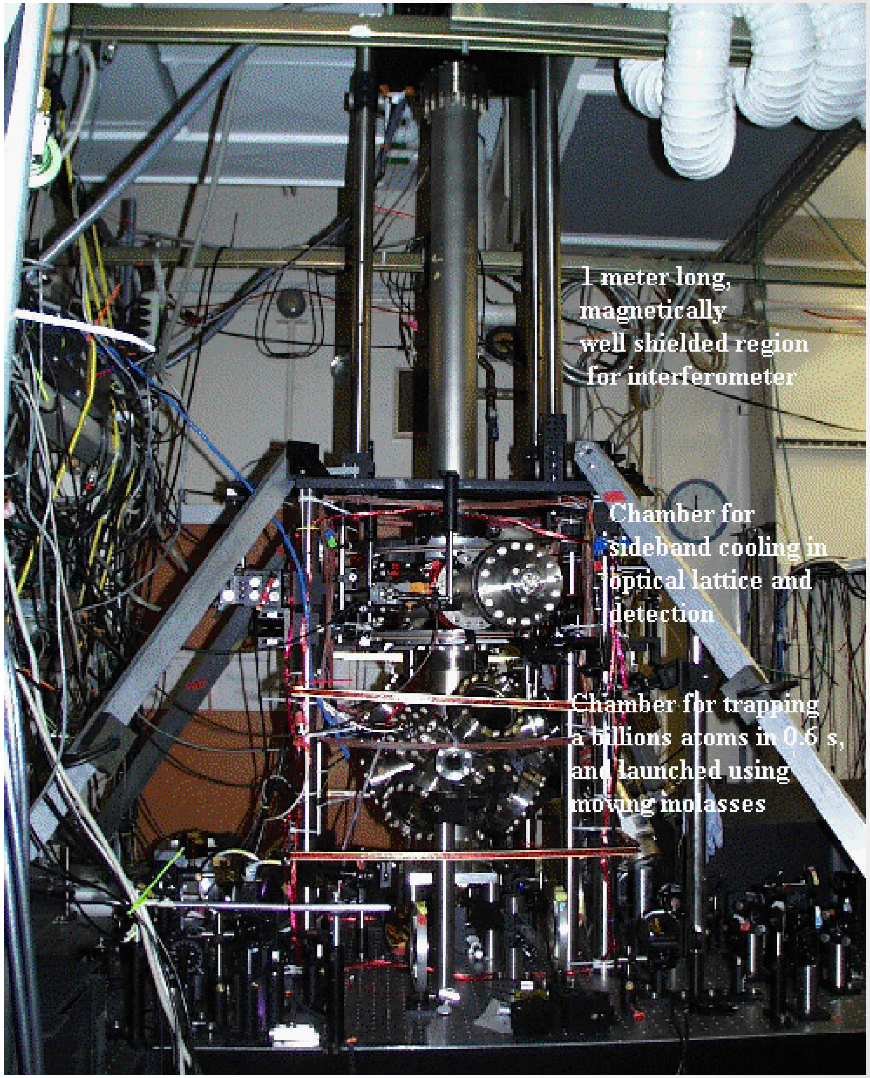
Light Pulse Atom Interferometry

- Precise momentum recoils
- Coherently separate atomic wavepackets in space, and recombine them.
- $\pi/2 \cdots \pi \cdots \pi/2$ pulse sequence.
- Extremely precise acceleration measurement.
  - Gravimetry
  - Seismology
  - Inertial Navigation



High Precision Gravity Measurements

- Ultracold atoms
- Fountain geometry
- $T \approx 100$ ms
- Sensitivity: ~5 ng/$\sqrt{Hz}$
- Data rate: ~1 Hz
- Size: ~m^3



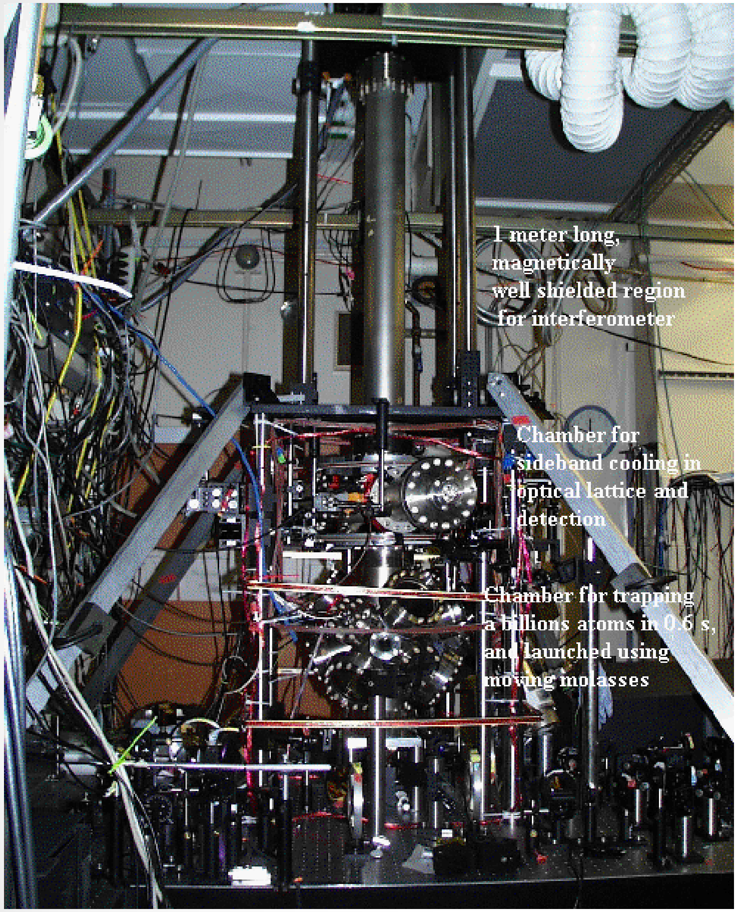
http://www.stanford.edu/group/chugroup/amo/interferometry.html

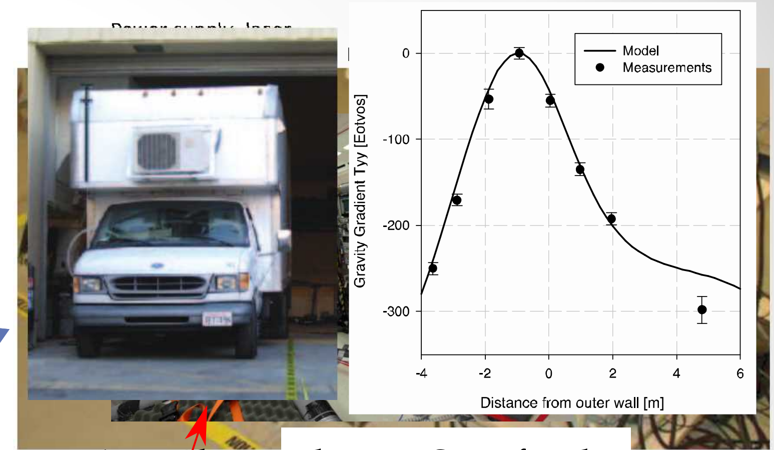
High Precision Gravity Measurements

- Ultracold atoms
- Fountain geometry
- $T \approx 1$ s
- Inferred Sensitivity: ~10 pg/$\sqrt{Hz}$
- Data rate: ~0.1 Hz
- Size: ~10 m^3

http://arxiv.org/abs/1305.1700

Light-Pulse Atom Interferometers

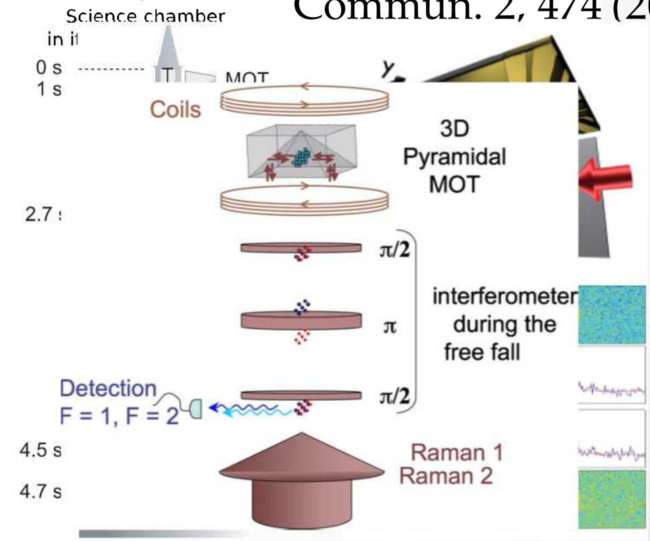




Wu, Ph.D. Thesis, Stanford 2009

Biedermann,

R. Geiger, et al., Nat. Commun. 2, 474 (2011)



Bodart, et al., Appl. Phys. Lett. 96, 134101 (2010)

H. Müntinga et al., Phys. Rev. Lett. 110, 093602 (2013)

Atom Interferometer Performance

- Advantages:
  - Record sensitivities
  - High bias stability

- Disadvantages:
  - Low data rate (~1 Hz)
  - Large and bulky (due to fountain geometry)
  - Low duty cycle due to MOT loading rate.

Can we maintain some of the advantages of atom interferometers while moving to higher data rates for "dynamic" applications?

- Examples:
  - Seismic sensing
  - Inertial navigation

High Bandwidth Atom Interferometer

- Use an atom interferometer with short time of flight.
  - Achieve ~100 Hz bandwidth?
  - Bias stability
  - Higher duty cycle
  - Large loss in sensitivity, due to T^2 scaling.

- Assume $N = 10^6, T = 4\ \text{ms}, R = 100\ \text{Hz}$
  - Sensitivity = 120 ng/$\sqrt{Hz}$

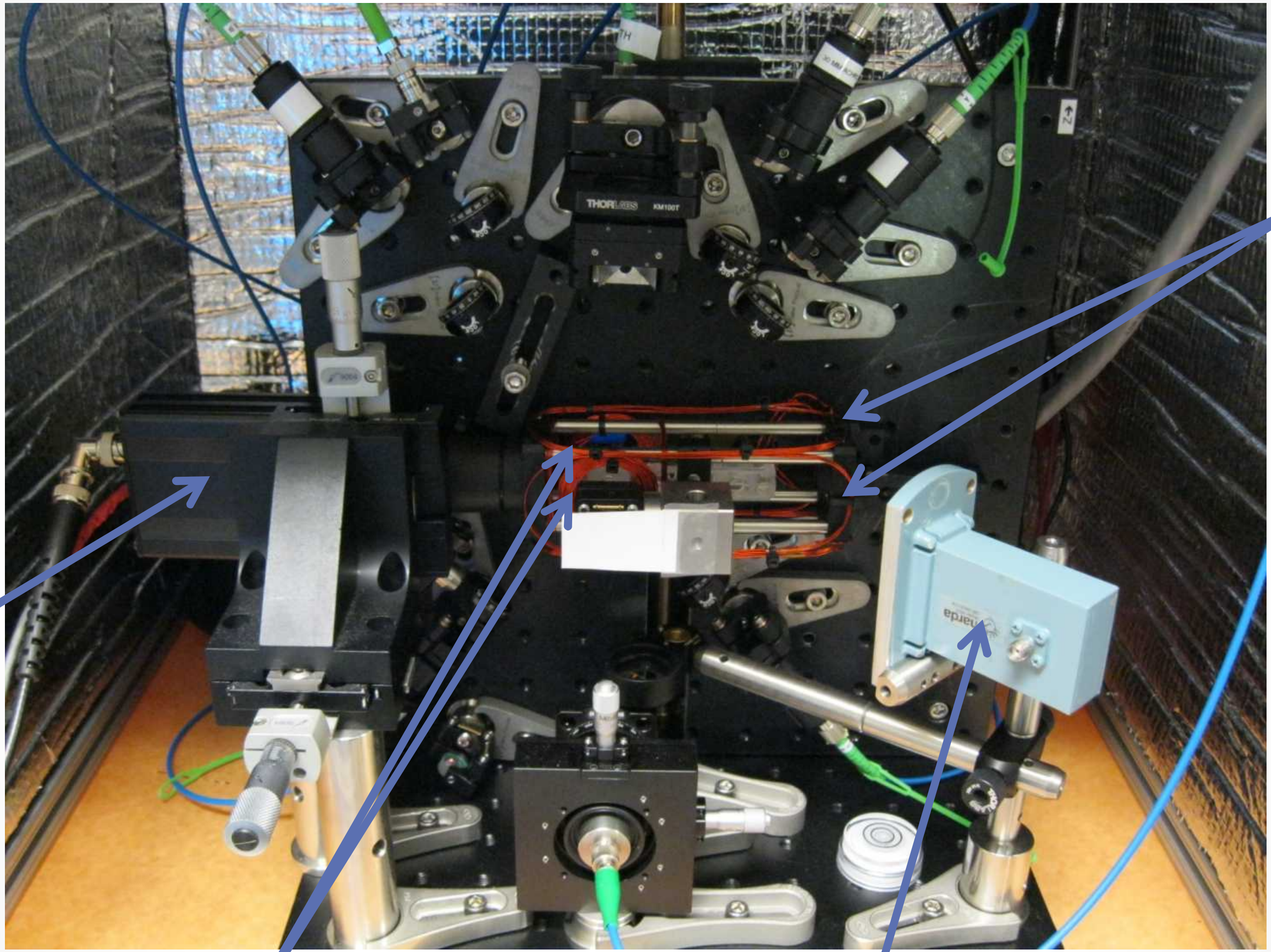
Experiment

Sample 100 Hz cycle:

- Start with atoms in MOT
- Drop atoms
- Polarization gradient cooling for 1 ms.
    - $T \approx 5\ \mu\mathrm{K}$
- Prepare atoms in F = 1 (0.1 ms)
- Raman pulse sequence (7 ms, T = 3.5 ms)
- Detect F=2 (0.1 ms)
- Detect Total (0.1 ms)
- Recapture (1.7 ms)

Sub D		Raman Interrogation		Recapture

Apparatus



Bias Coils

APD

Trapping Coils

Microwave horn (diagnostic)

Recapture Efficiency

- Reload the MOT freshly from vapor shot to shot.
  - This process is *slow*. ~100's of milliseconds.
  - Exponential decay curve.

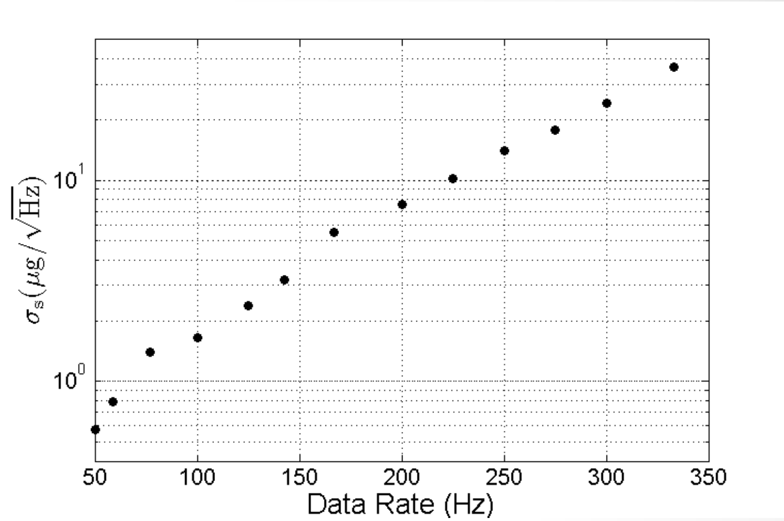
- A short time of flight allows for recapture.

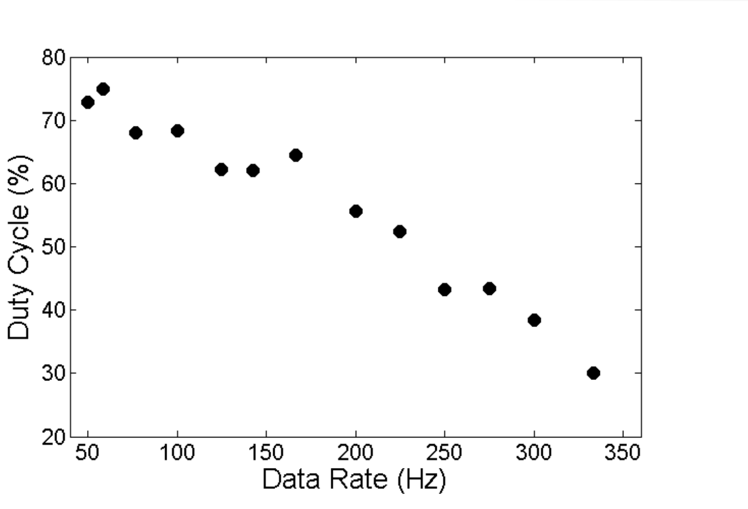
- Previous cycle: 2 x 10^5 atoms. 1.7 ms recapture time, 92% recapture efficiency.
  - Loading from vapor: > 20 ms.

- Fractional recapture of previous cloud with a constant loading rate from vapor.

Performance

- For each bandwidth, there is an optimal interrogation time.
- 0.6 $\mu g/\sqrt{Hz}$ at 50 Hz to 37 $\mu g/\sqrt{Hz}$ at 330 Hz.
- Optimal duty cycle: 75% to 30%.
- Phase noise: consistently ~30 mrad/shot.
  - Noise sources: Raman phase noise, B-field.

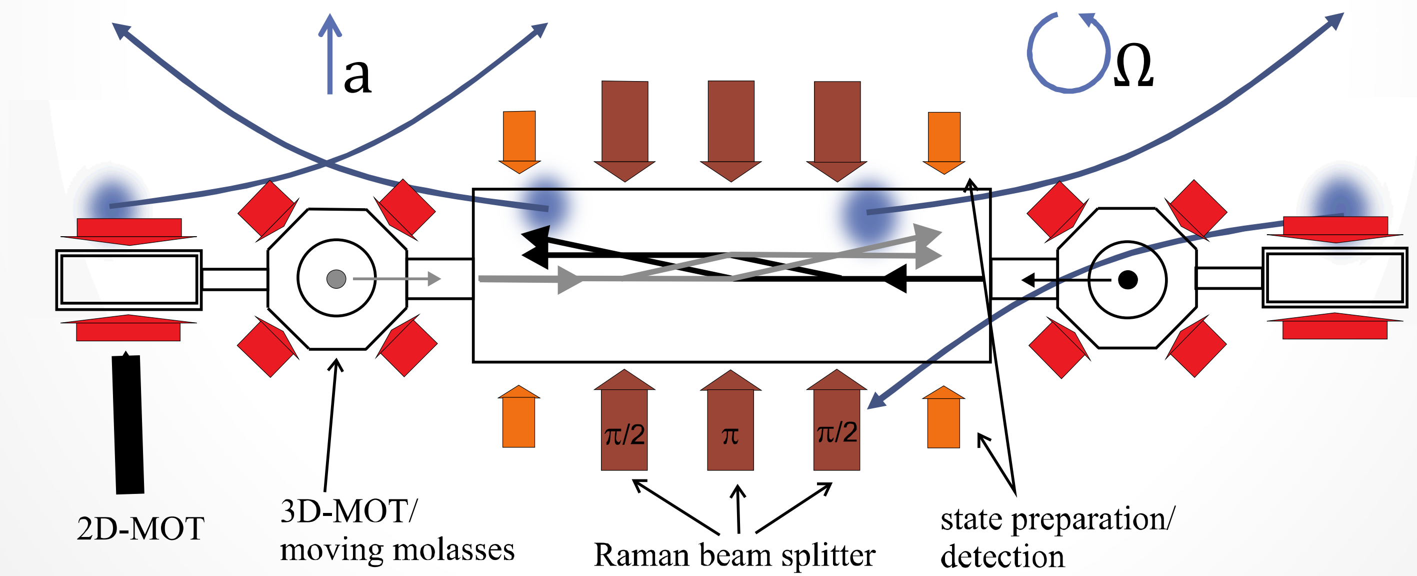




H. McGuinness, A. Rakholia, G. Biedermann
Appl. Phys. Lett. **100**, 011102 (2012)

Rotation Measurement

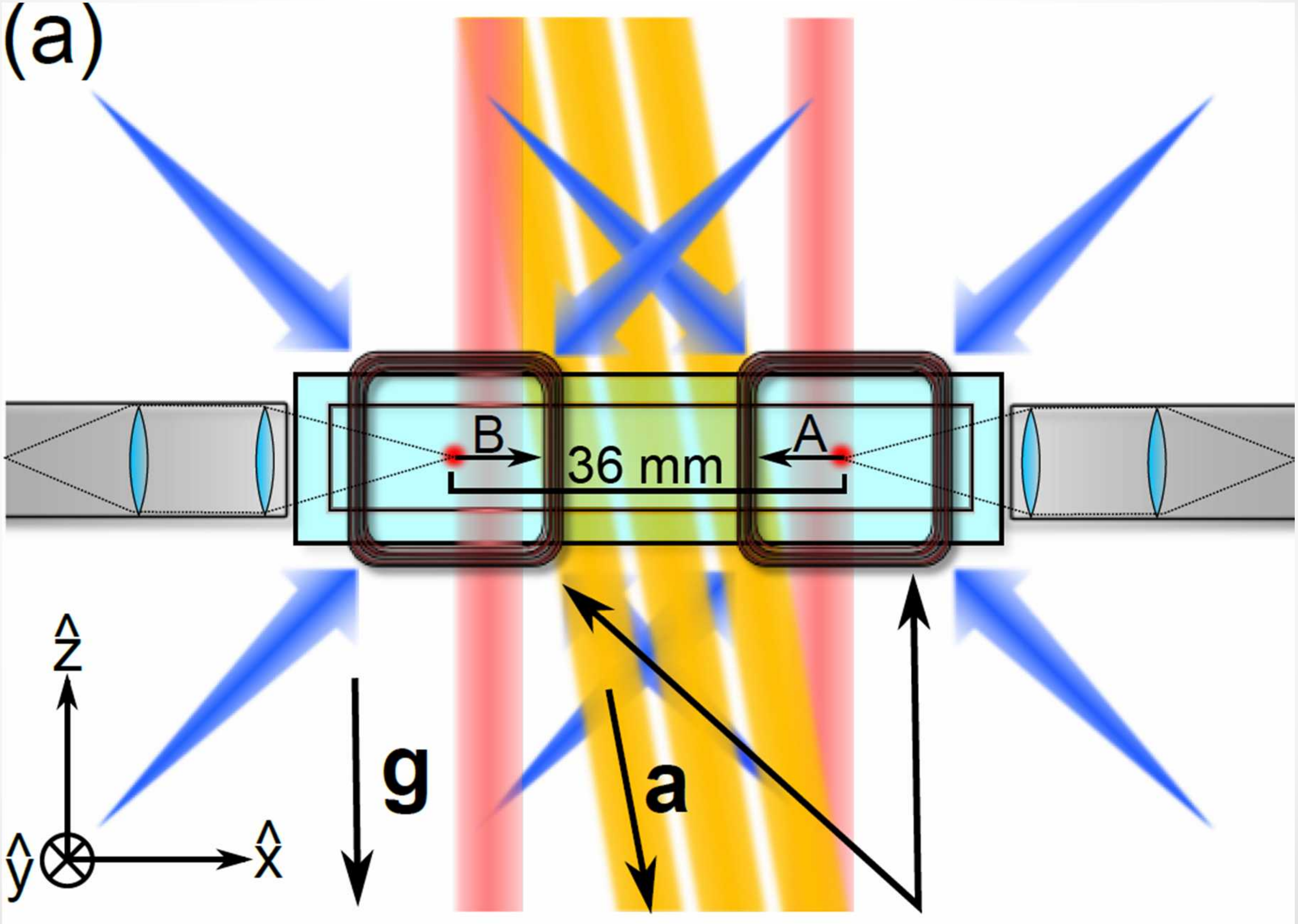
- Inertial navigation requires acceleration and rotation.
- Non-zero initial velocity: $\Delta\phi = \boldsymbol{k_e} \cdot (\boldsymbol{g} - \boldsymbol{2v} \times \boldsymbol{\Omega})T^2$
  - Single interferometer insufficient
  - Recapture is problematic with high initial velocity.
- Two interferometers with equal and opposite initial velocities.
  - Sum signals for acceleration, and take the difference for rotation.



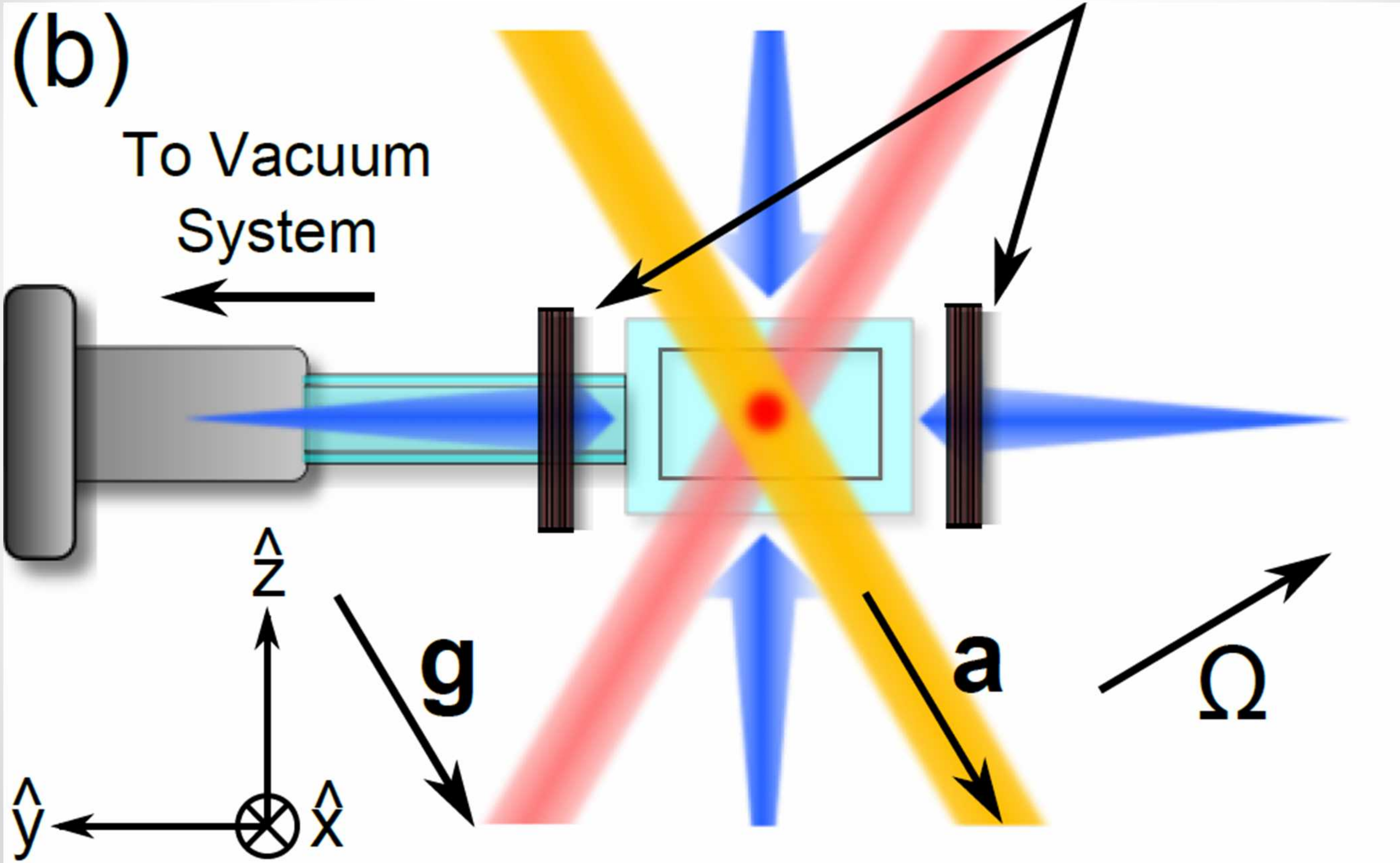
T. Müller, et al., Eur. Phys. J. D **53**, 273-281 (2009)

Exchange MOT

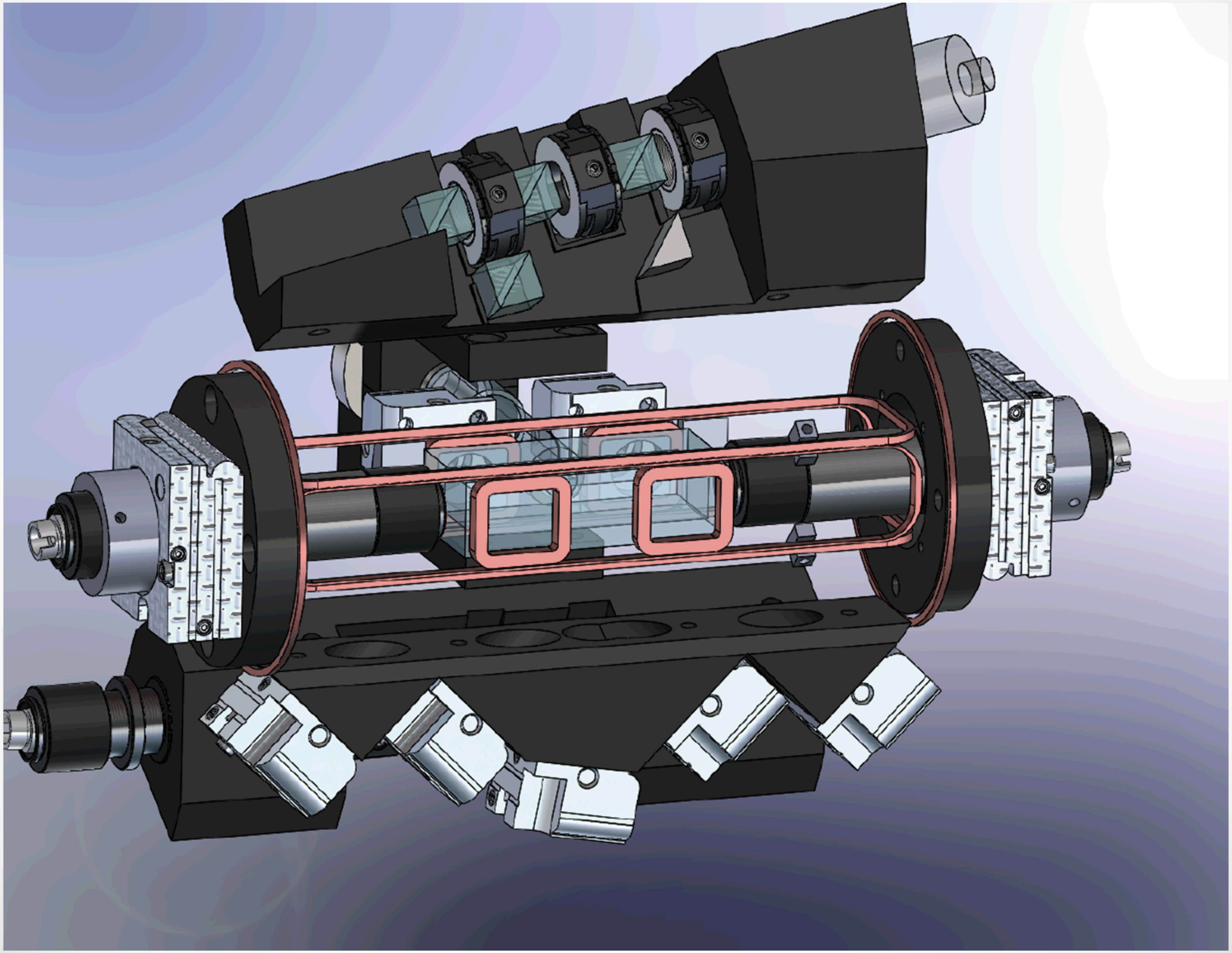
Apparatus



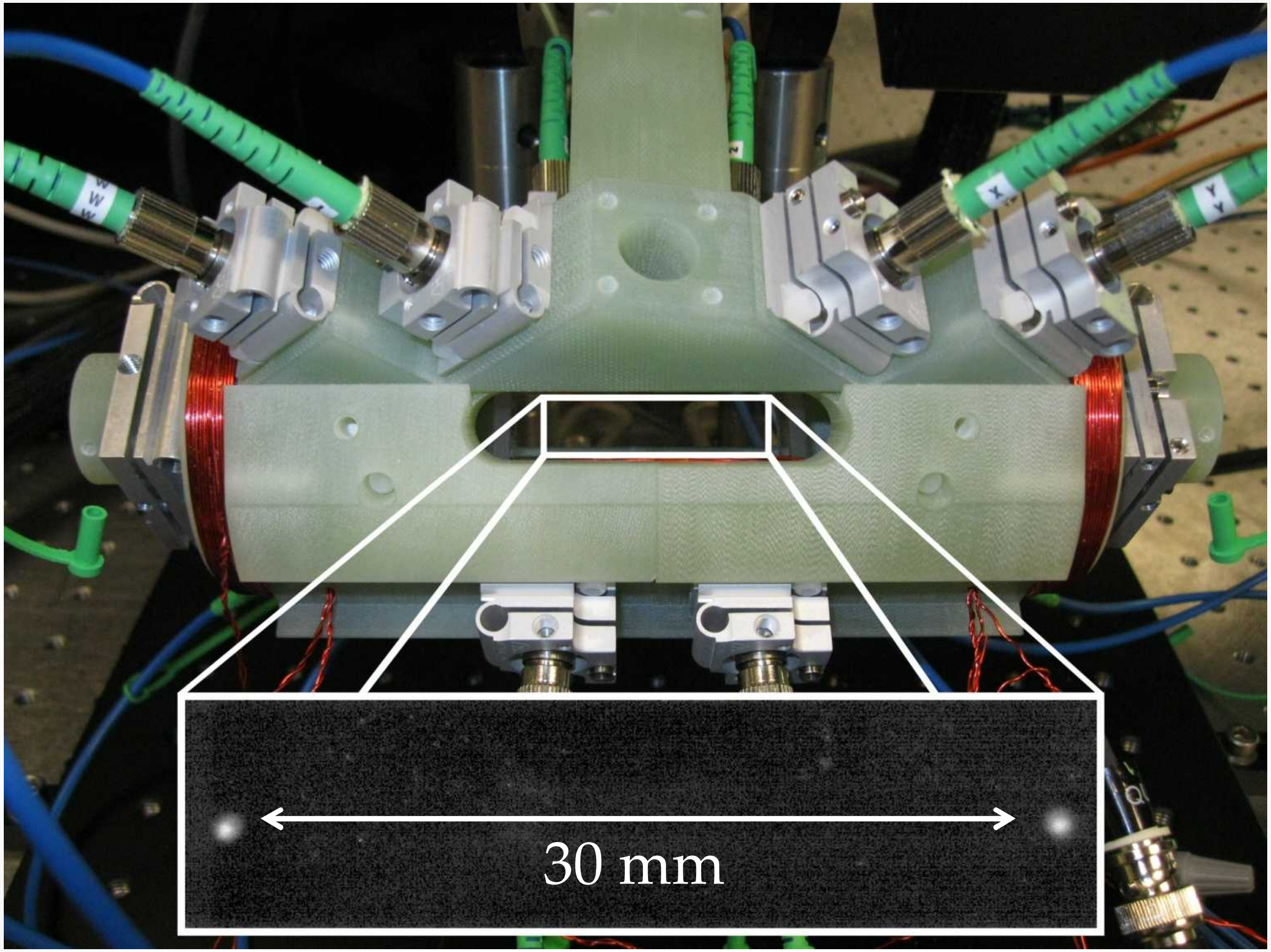
Apparatus



Apparatus

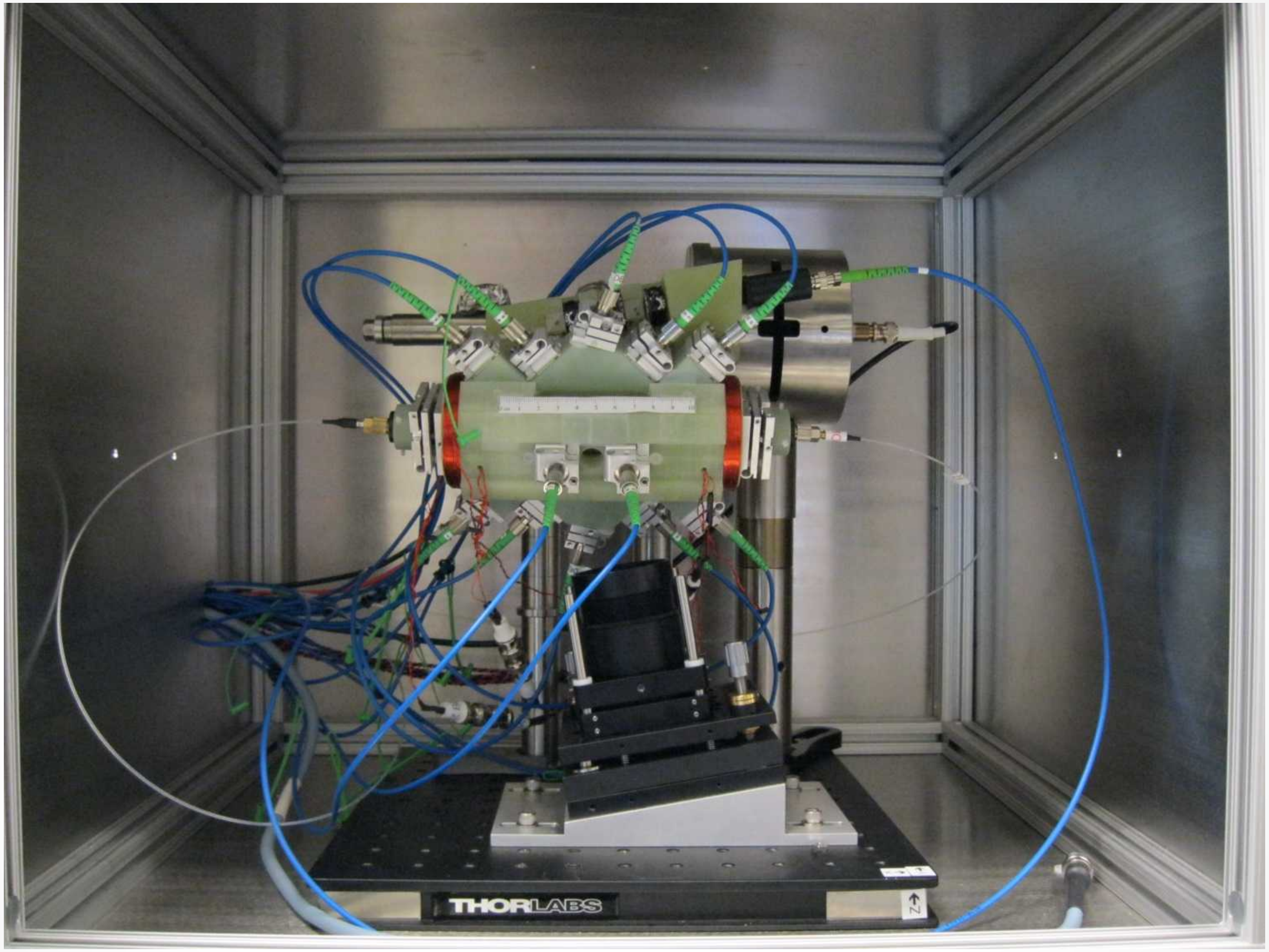


Apparatus



Mot Exchange DUal axis Sensor with Atom interferometry

Apparatus



Mot Exchange DUal axis Sensor with Atom interferometry

Medusa

Cycle time: 12.5 ms (80 Hz)

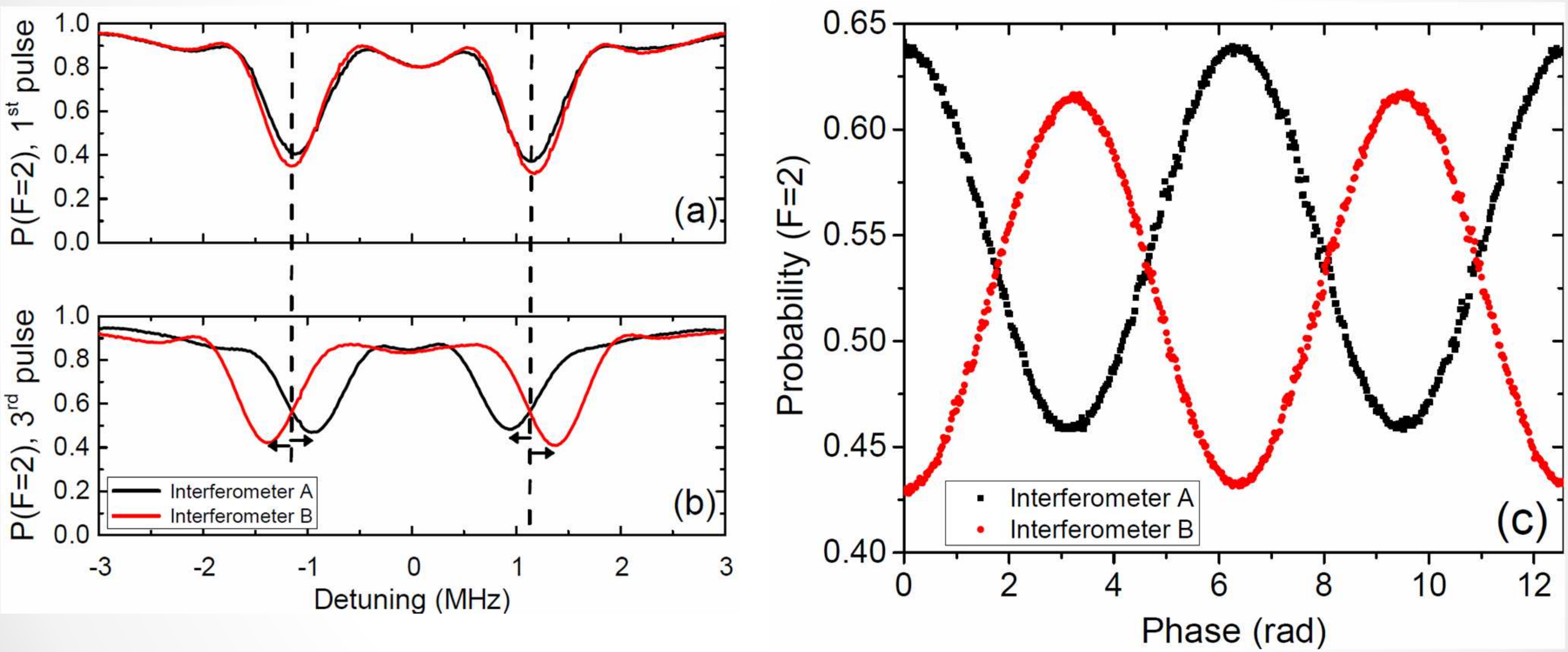
Launch	Flight	Recapture
2 ms	6.5 ms	4 ms

Medusa

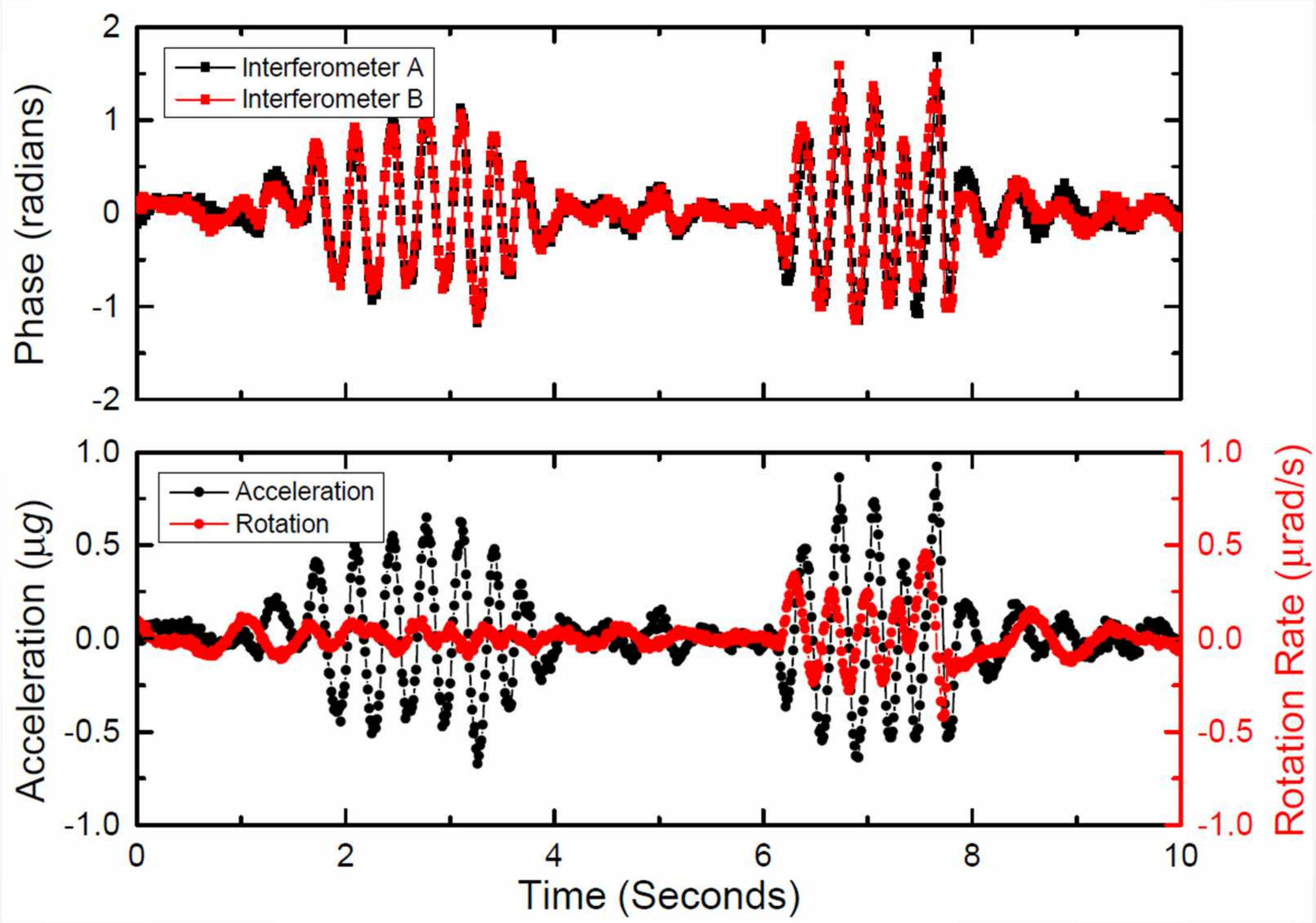
Cycle time: 12.5 ms (80 Hz)

Launch	Flight	Recapture
2 ms	6.5 ms	4 ms

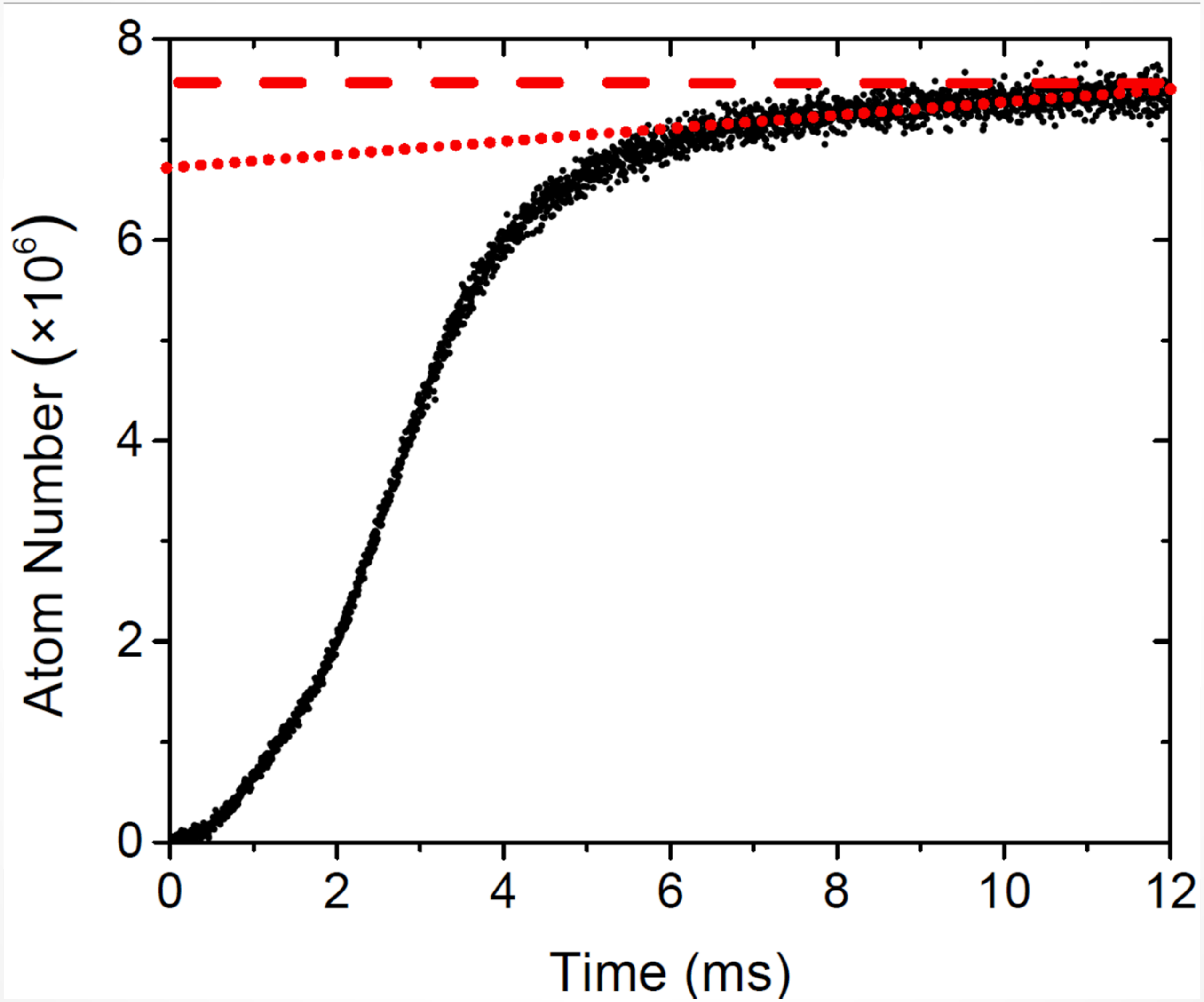
Interferometer



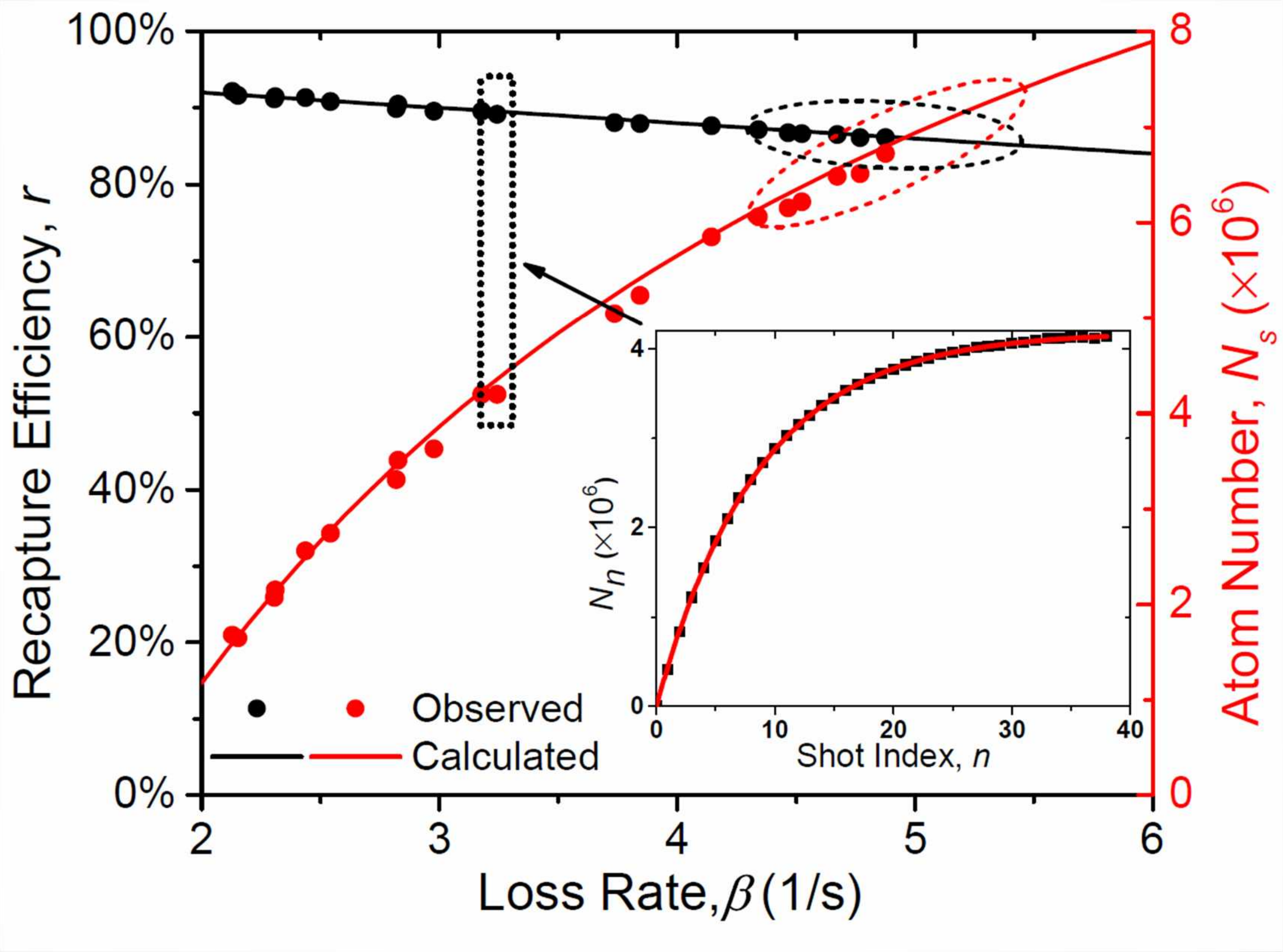
Interferometer



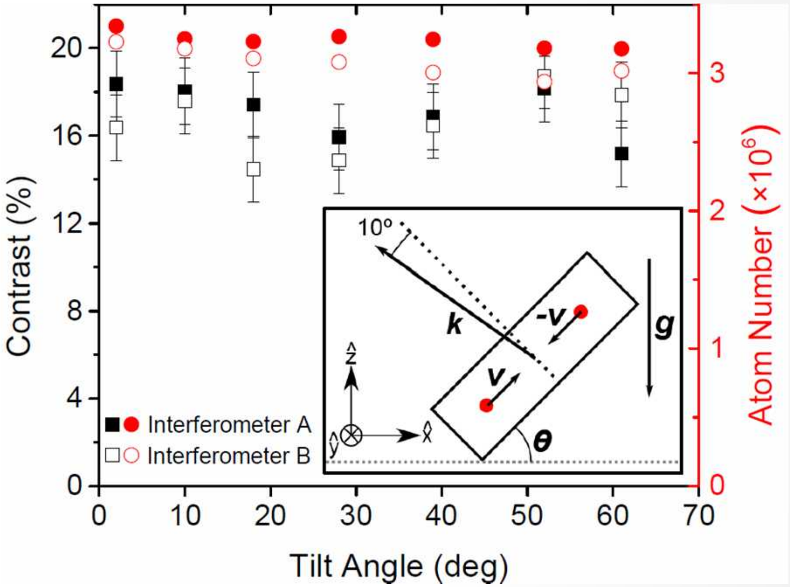
Recapture



Recapture

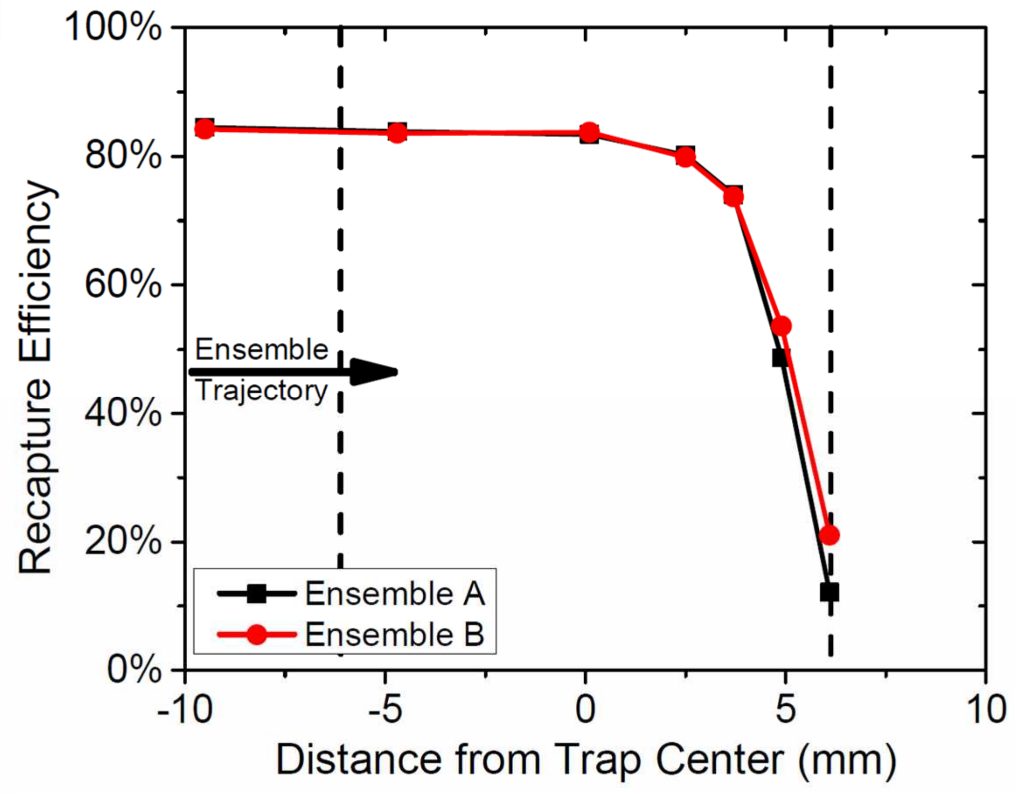

100%
80%
60%
40%
20%
0%
Recapture Efficiency, r
8
6
4
2
0
Atom Number, N_s (×10^6)
2
3
4
5
6
Loss Rate, β (1/s)
Observed
Calculated
N_n (×10^6)
4
2
0
0
10
20
30
40
Shot Index, n

Tilt Test



Contrast (%)
Atom Number (×10^6)
Tilt Angle (deg)
Interferometer A
Interferometer B
10°
k
-v
v
g
θ

Recapture Test



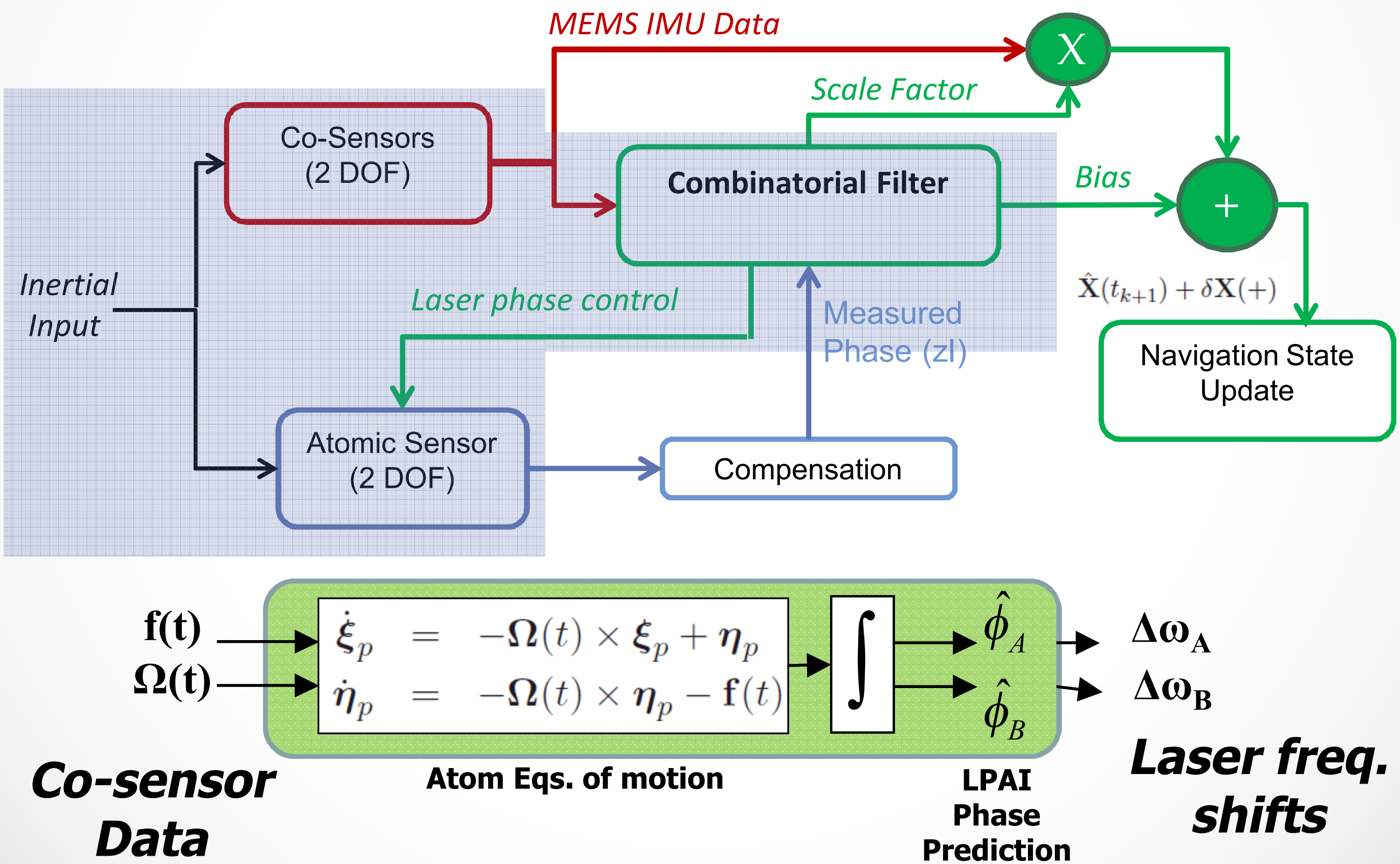
~10 *g*, 20 rad/s

Improvements

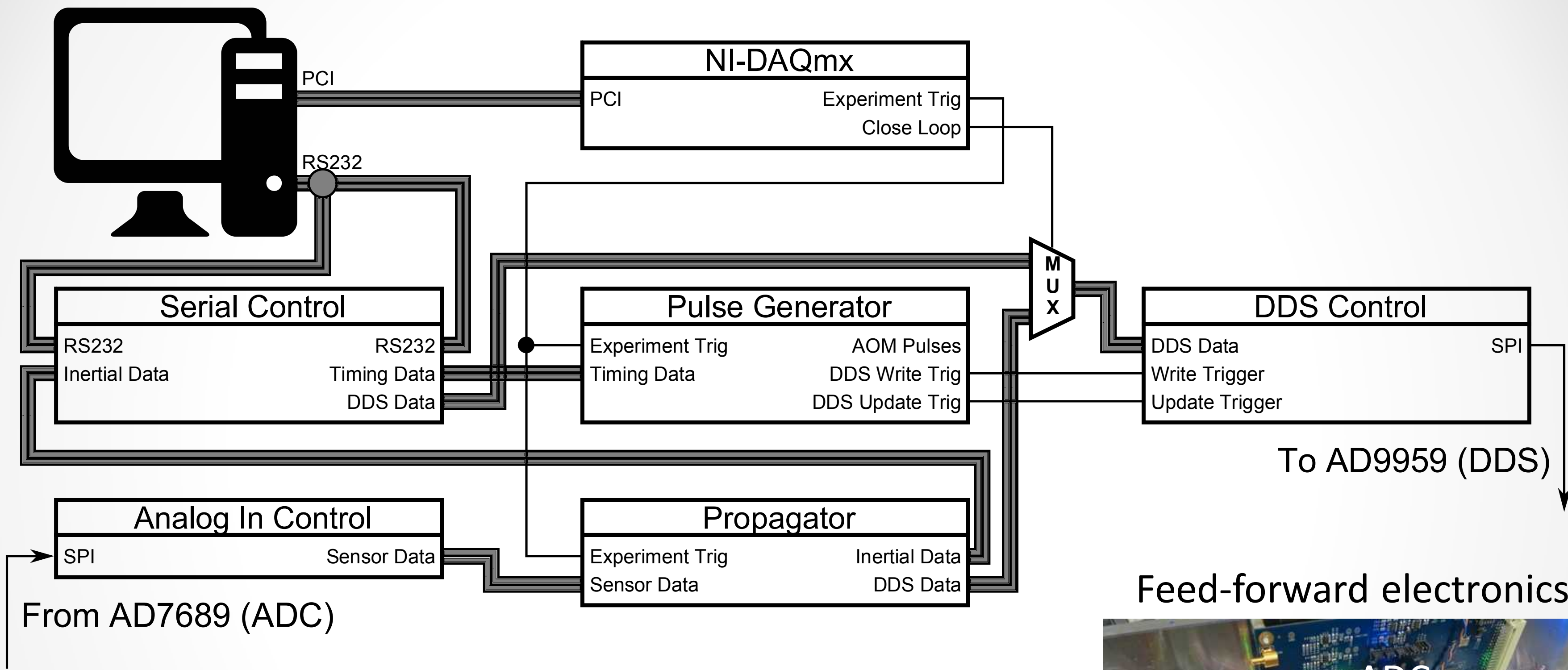
- Optimize sensitivity, bias stability, bandwidth, recapture.
- Demonstrate dynamic nature.
- Numerical simulations for MOT recapture and launching dynamics.
- Discuss compact laser system.
- Evaluate performance for applications.

Technical challenge

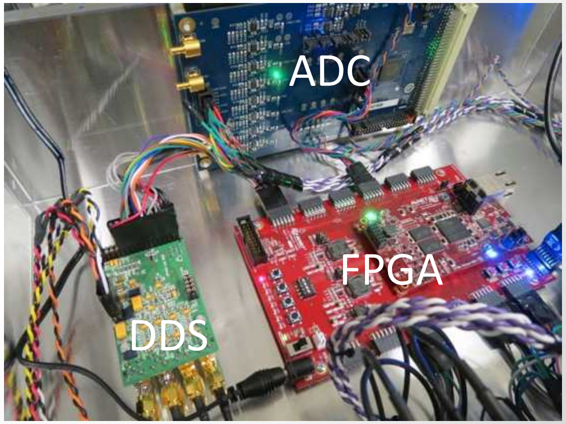
- Real-time cosensor read, Runge-Kutta propagator calculation, and phase/frequency write to interferometer laser in less than 0.5 ms (note: T = 4.5 ms)



Control hardware

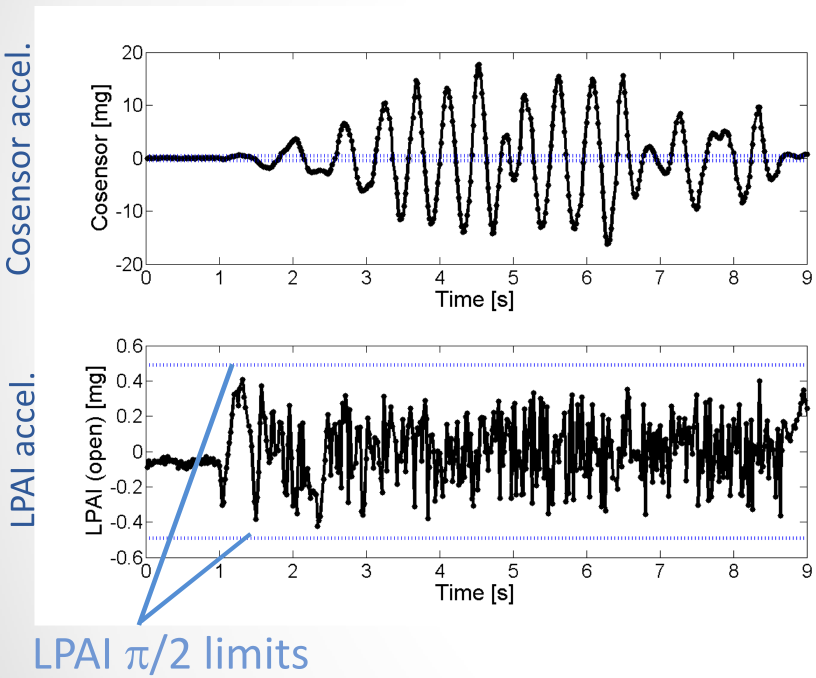


Feed-forward electronics

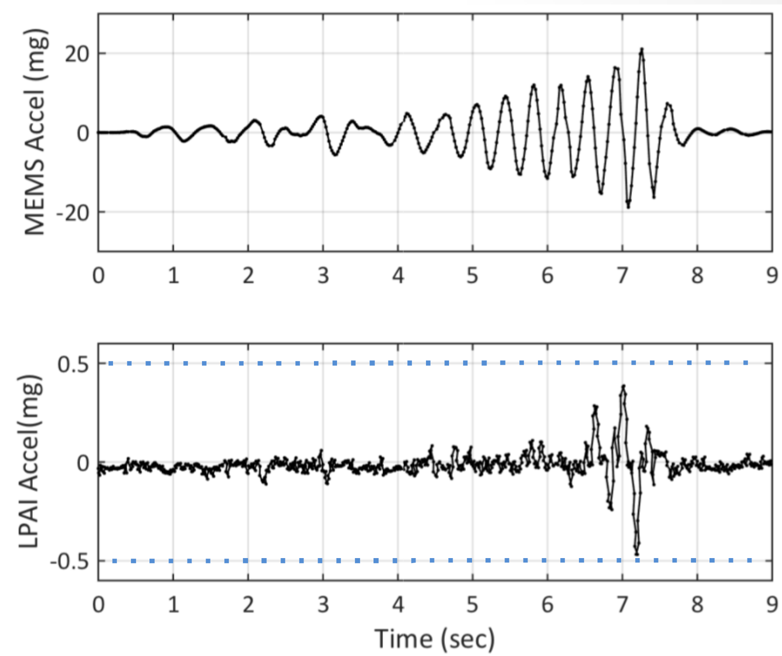


results

OPEN LOOP



FEED FORWARD



Initial results:

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

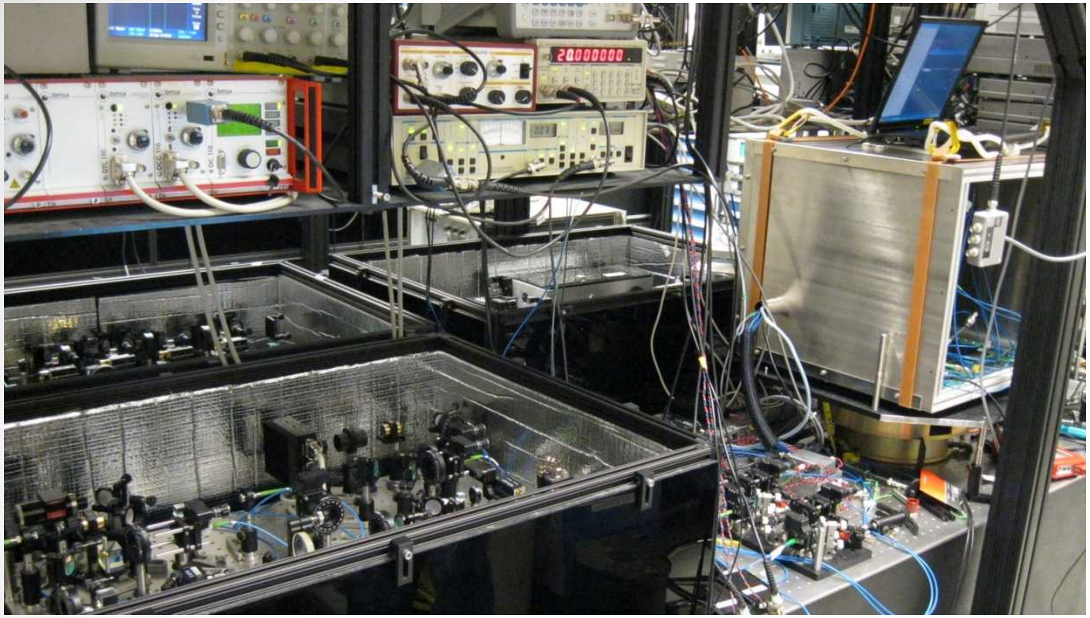
CSCAN

- "Chip-Scale Combinatorial Atomic Navigator"
  - DARPA Inertial Sensor Proposal

- Requirements:
  - "Volume of no more than 20 cubic centimeters"
  - "power consumption of no more than 1 Watt"
  - "10^{-4} deg/hour for rotation"
  - "10^{-6} g for linear acceleration"

- Atom Interferometry?
  - Proposal emphasizes stability ✓
  - Power (100s of W) ✖
  - Volume ($\sim 10^6$ cc) ✖

Exploring ultra-short T



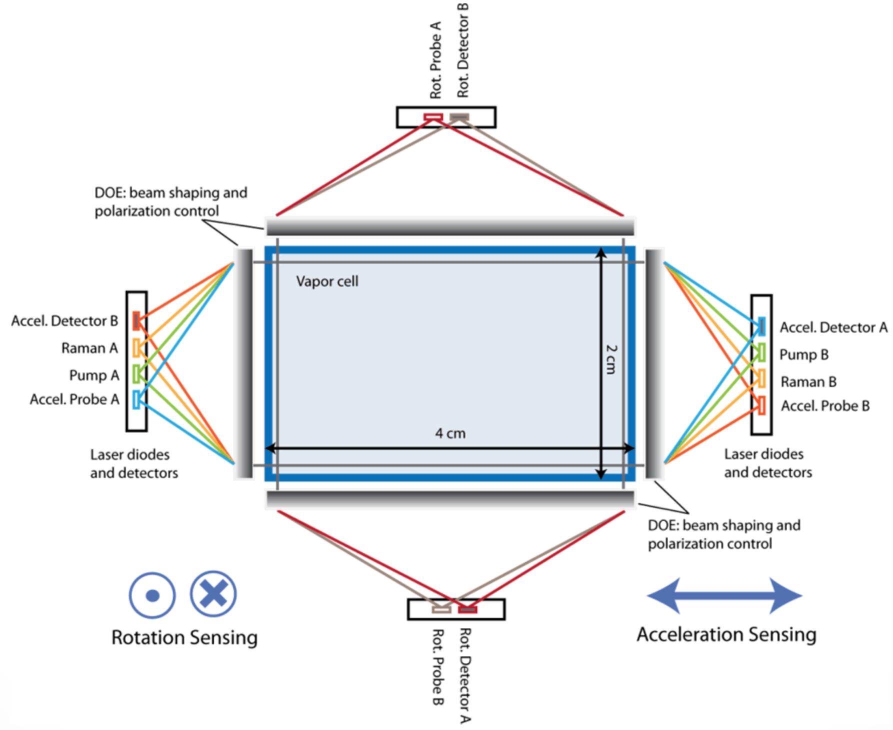
Sandia atom interferometer
- Laser cooled ensemble
- >1,000,000 cc

- 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

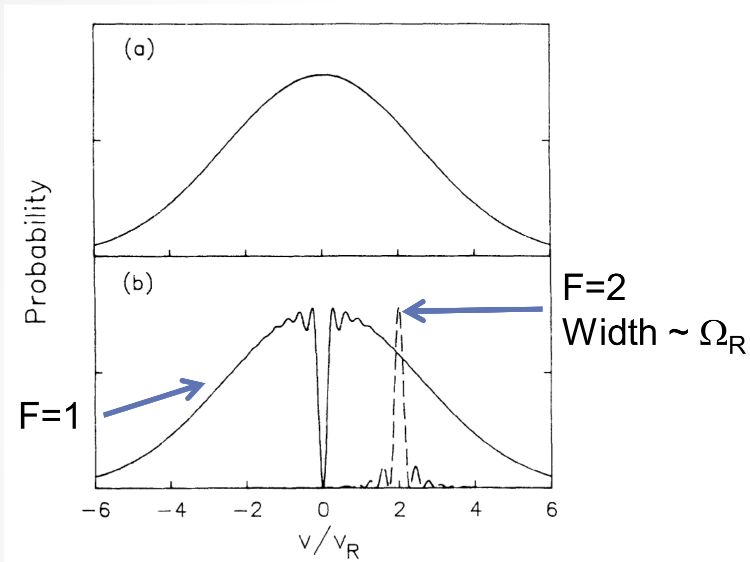
Warm vapor concept

- 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



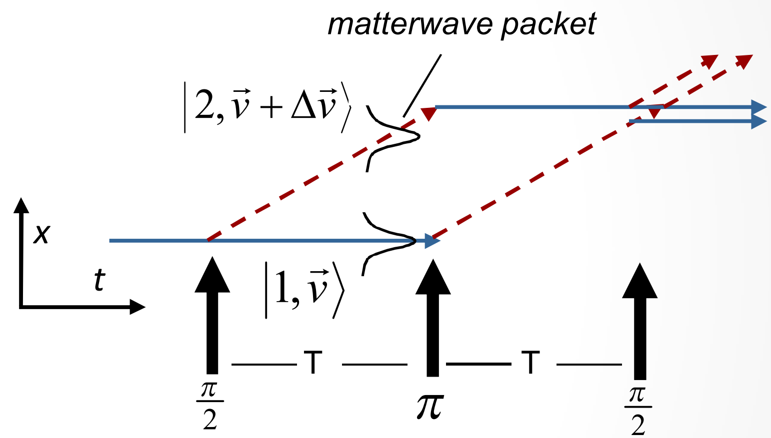
Motivation: potentially highly compact and simplified. Conceptual diagram (not to scale) of a 2-axis atomic sensor.

Velocity selectivity of Raman pulse



Result of Raman transition used for LPAI

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



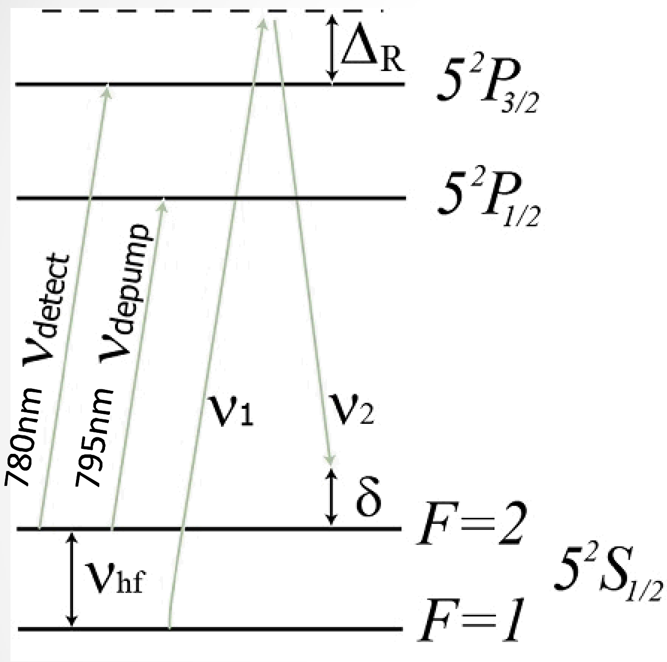
Analyze in momentum space

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

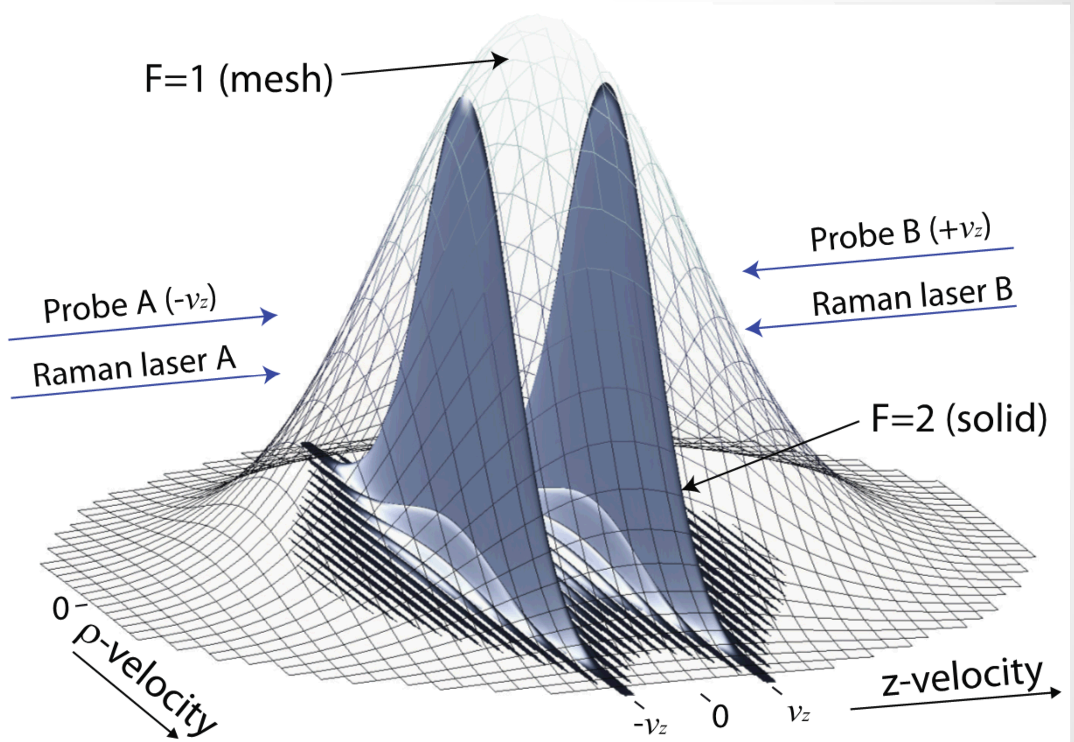
$$\Delta\phi = \mathbf{k}_{\mathrm{eff}} \cdot (\mathbf{g} - \mathbf{2v} \times \mathbf{\Omega})\mathbf{T}^2$$

Warm vapor atom interferometer

Ultra-short T



Simplified laser frequency requirements: potential for miniaturization



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

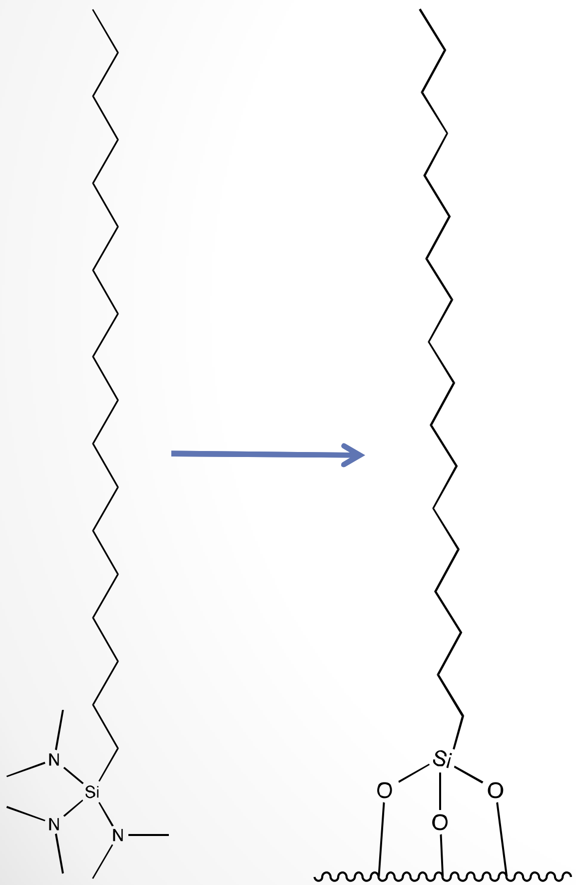
State preparation

To eliminate background signal, must depump all velocity classes

In-house coating development

Tris(N,N-dimethylamino)octadecylsilane

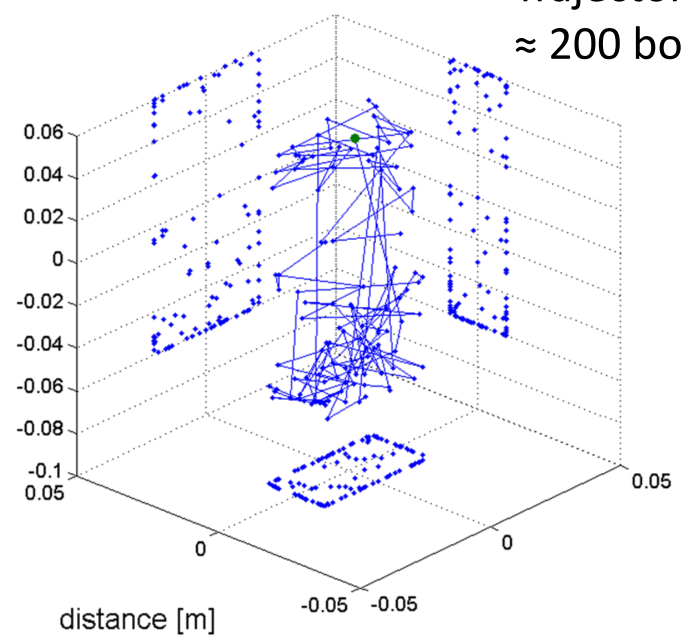
measured: τ = 23 ms hyperfine state lifetime



Idealized Bonding

Trajectory simulation

≈ 200 bounces



Must be inertially pure—no collisions!

Coating outgassing < 10^{-4} Torr

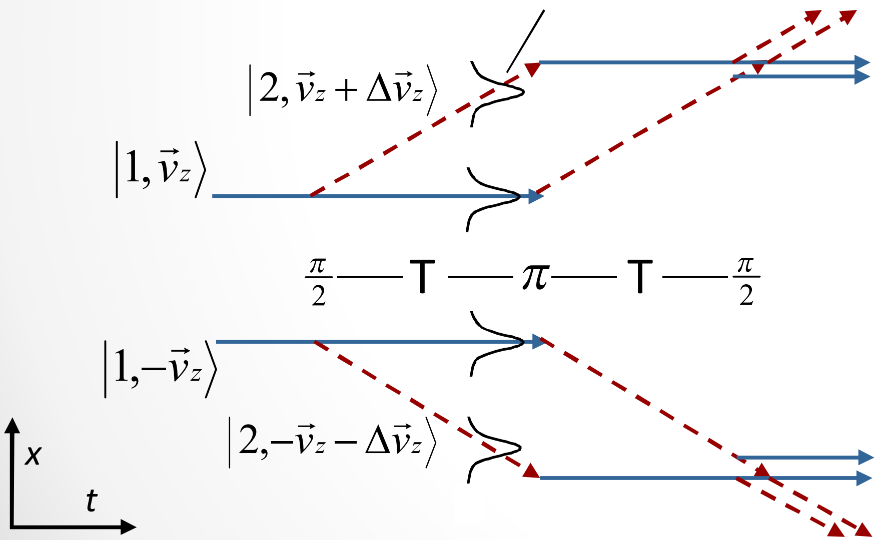
No buffer gas

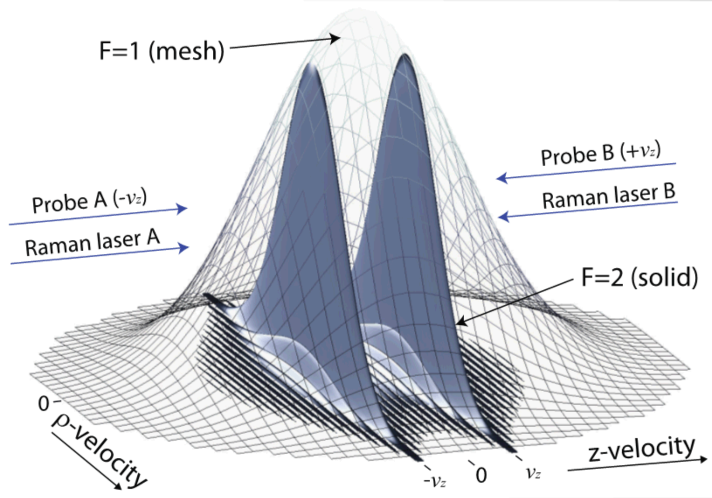
Simultaneous interferometers

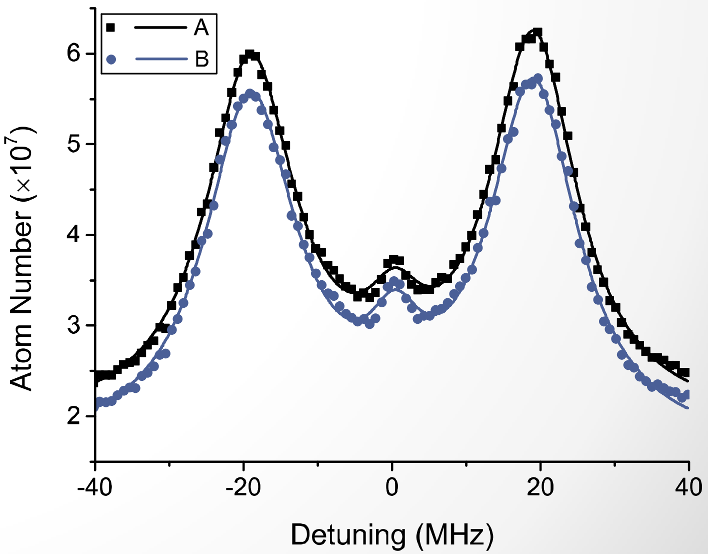
Common mode noise rejection

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

Simultaneous interferometers



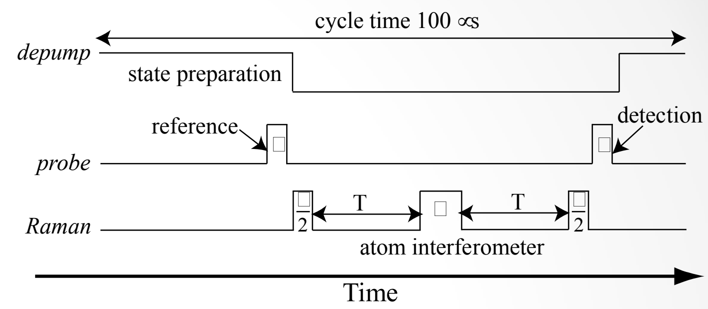


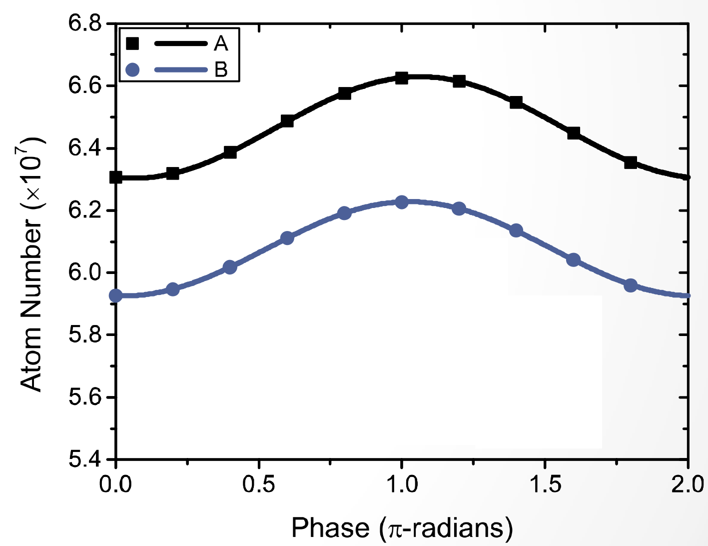


Simultaneous interferometers

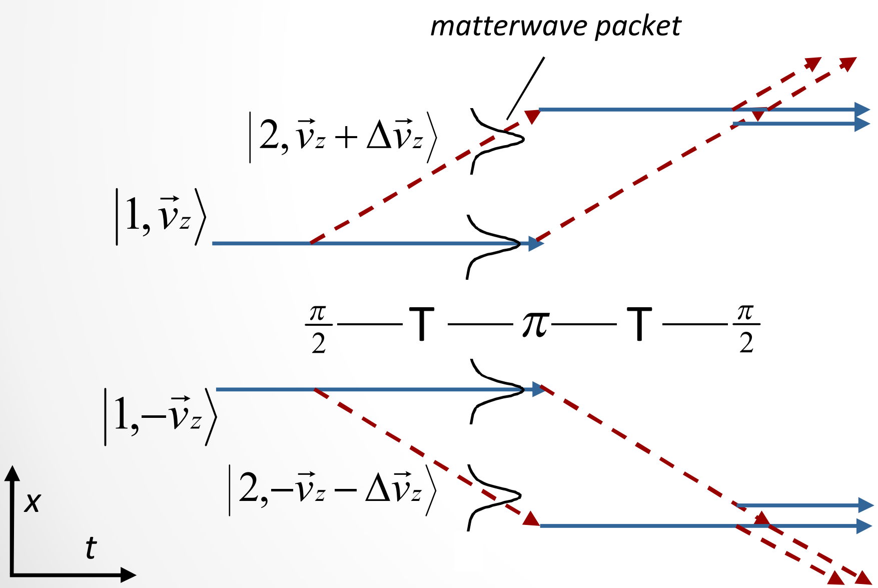
Common mode noise rejection

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





Simultaneous interferometers

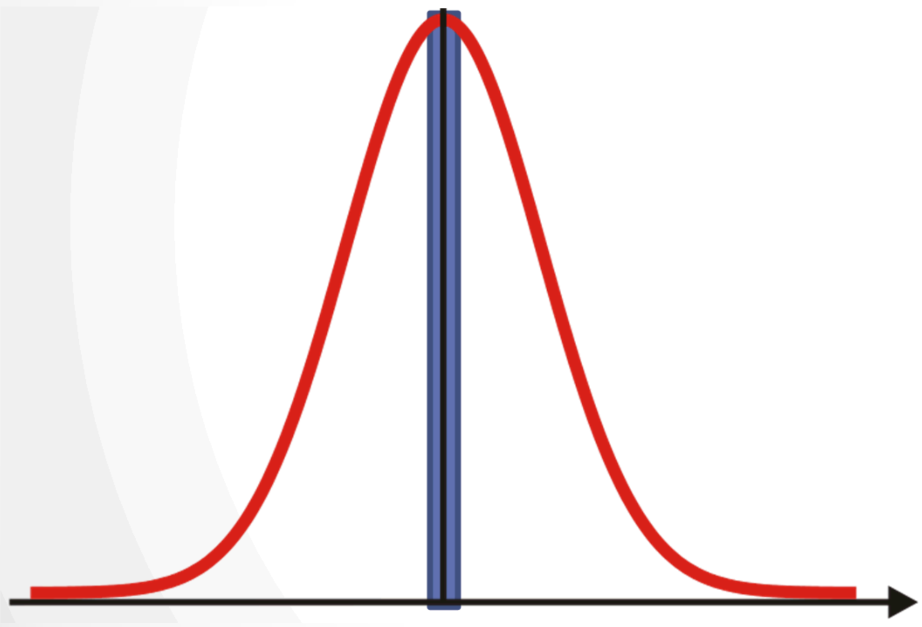


Measured:

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

Vapor Cell Atom Interferometer

- Warm Vapor Cell Atom Interferometer
  - Room temperature gas has SOME "cold" atoms
  - Linewidth of D2 transition addresses 50 mK.



$v \sim 2$ m/s (50 mK)

$V \sim 1\ \mathrm{cm}^3$

T ~ 10 μs

$T \sim 70\ °\mathrm{C}$ ($P \sim 10^{-5}$ torr)

Total N ~ 10^{12}

Cold N = 0.5% × Total N

~ 10^8

$\delta\phi \sim 0.1$ mRad/shot

$\delta g \sim 50\ \mu\mathrm{g}/\sqrt{\mathrm{Hz}}$

Vapor Cell Atom Interferometer

- Advantages:
  - Simple laser system
  - Small sensor head
  - Light vacuum requirements

- Disadvantages:
  - Need LOTS of Raman power (but pulsed)
    - Kasevich: 20 W, 780 nm amplifiers [1]
  - 0.1 mRad/shot is tricky, quiet detection/electronics

- Progress:
  - Observation of fringes

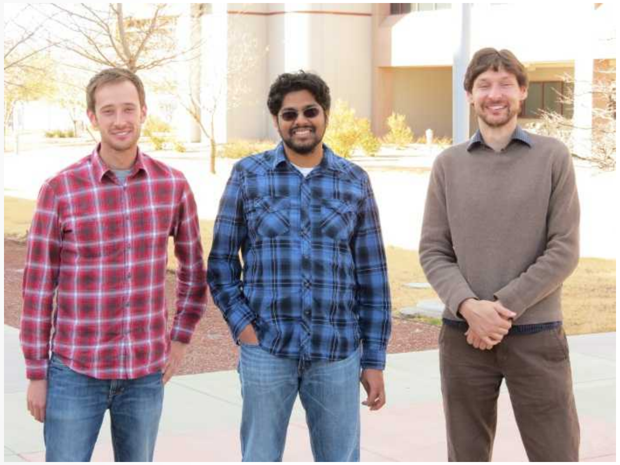
[1] S.-W. Chiow, T. Kovachy, J. M. Hogan, M. Kasevich, Opt. Lett. 37, 3861-3863 (2012).

Conclusion

- Demonstrated an atom interferometer accelerometer operating between 50 and 330 Hz
  - Rivals performance of inertial-grade sensors.
- Demonstrated the exchange-MOT concept and small physics package.
  - Volume: ~3 liters
  - 4.5 m/s launch velocity, 80 Hz bandwidth.
- Demonstrated acceleration and gyroscopic measurement.
  - Sensitivities suitable for wide variety of applications.
- Vapor cell accelerometer for DARPA CSCAN.

Acknowledgements

- Grant Biedermann, PI
- Hayden McGuinness, Postdoc
- Neutral atom group at Sandia National Laboratories



G. Biedermann, A. Rakholia, H. McGuinness

This work was funded by the Laboratory Directed Research and Development (LDRD) Program. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Questions?