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Atomic Clock and Atom Interferometer Development at Sandia National Laboratories

Grant Biedermann and Peter Schwindt

September 28th, 2011

Atom Interferometer*

Funding LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Atomic Clock—IMPACT

Funding DARPA

Collaborators JPL Jet Propulsion Laboratory California Institute of Technology; Symmetricom

*Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

AI acceleration measurement

Use atom to stroboscopically measure position (optical phase) at three equal-spaced points in time

$$\varphi_i = \vec{k}_{eff} \cdot \vec{x}_i$$

calculate curvature via finite difference method

$$\Delta\varphi = \varphi_1 - 2\varphi_2 + \varphi_3$$

…and then

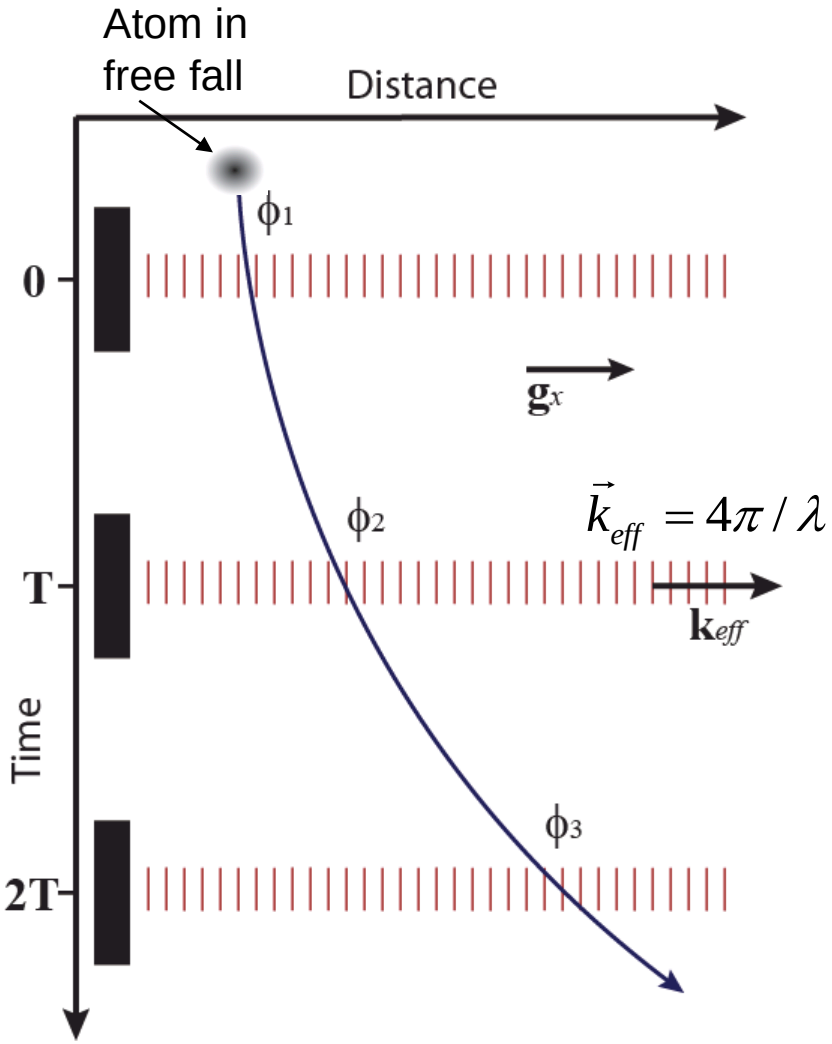
$$g_x = \frac{\Delta\varphi}{k_{eff} T^2}$$

References stable laser

- long term stable and accurate

Ramifications of high data rate

- Reduced T…reduced sensitivity



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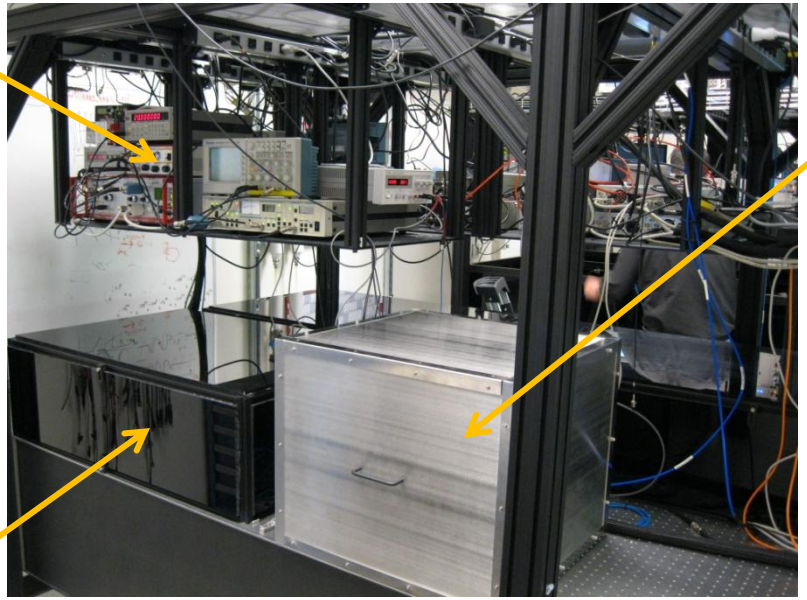
Apparatus

Control electronics



Lasers/optomechanics

Atom interferometer

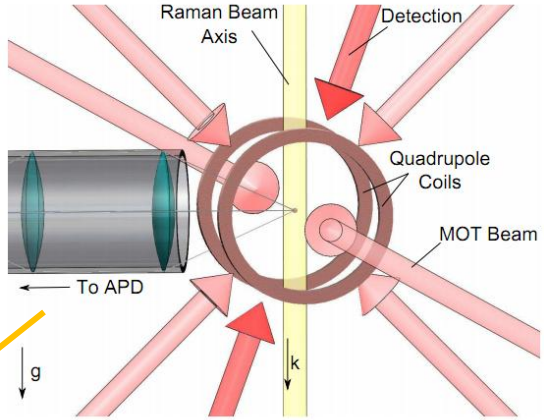


FIG. 1. Diagram of the interferometer setup. The quadrupole coils are 32 mm in diameter.

78 mm

UHV cell

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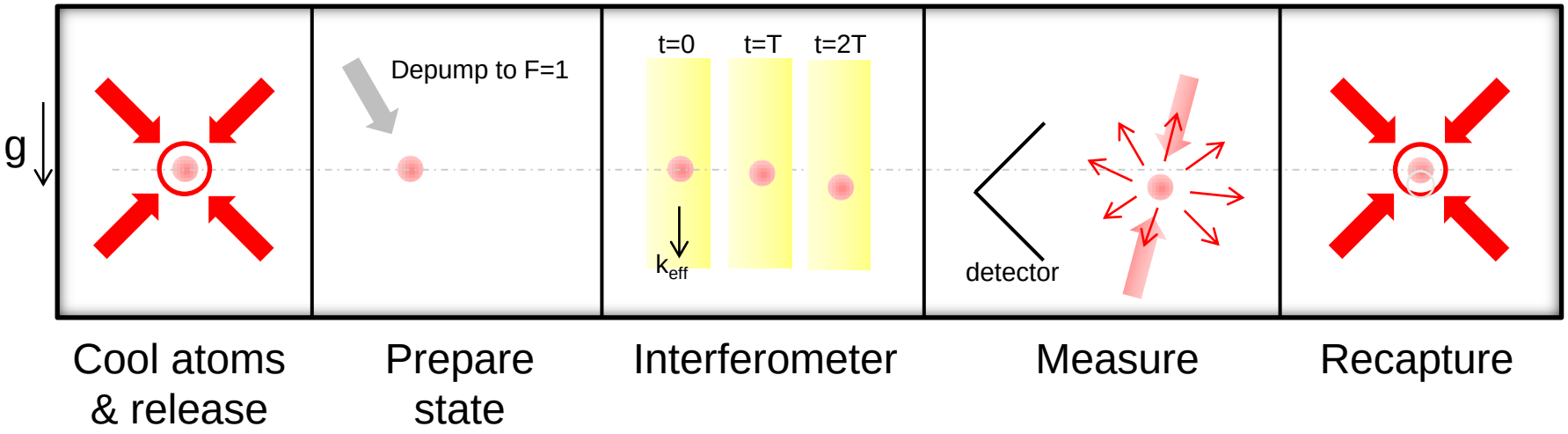
High data-rate technique

- Background loading rate 4 x 10^4 atoms/ms
  - Limited by beam size and vapor pressure
  - Limits data rate—recapture

- Recapture cycle



- Achieves data rates of 330 Hz
- Maintains atom # of 2 x 10^5

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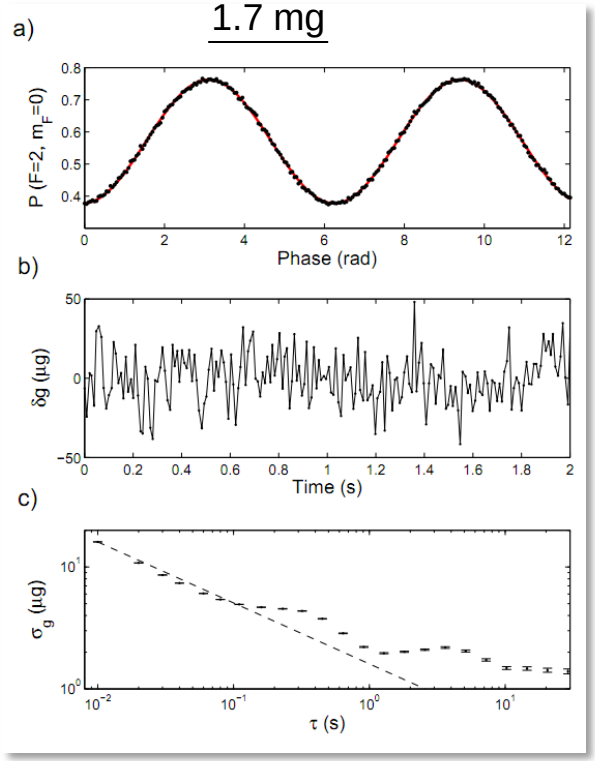
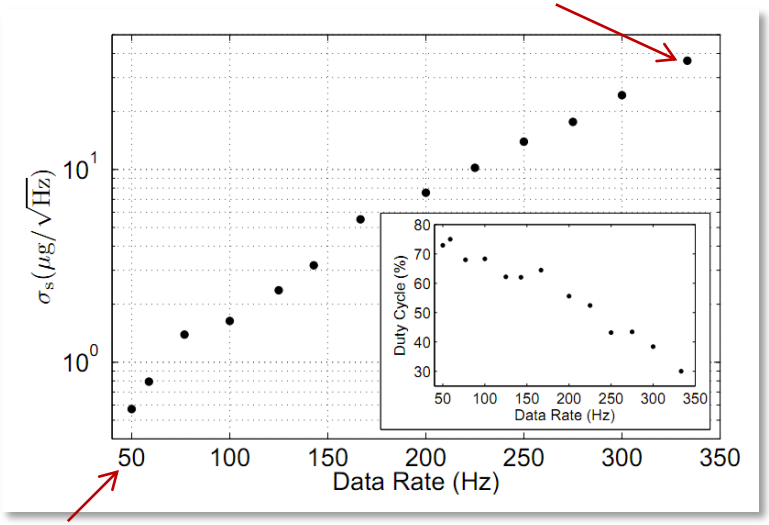
High data-rate atom interferometer

http://arxiv.org/abs/1109.4610

Acknowledgements: Hayden McGuinness
Akash Rakholia





T = 3.4 ms
1.6 μg/Hz$^{1/2}$
100 Hz data rate

Best reported gravimeter — 8 ng/rtHz, 0.53 Hz
Mueller et al., PRL, 0311011 (2008)

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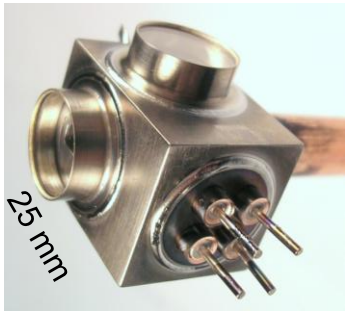
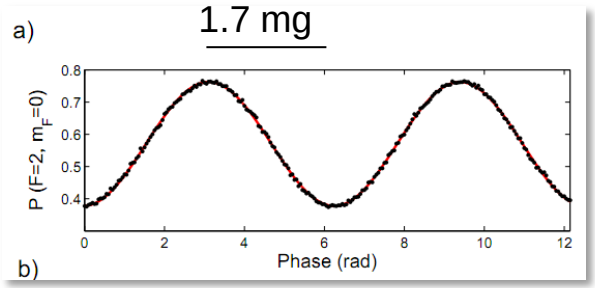
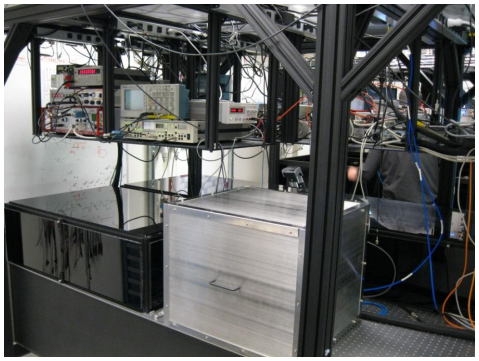
Challenges

- Integrated, vibration immune optical system
- Low-power, frequency tunable, switchable laser source
- Compact and rugged vacuum systems
- High jerk—dynamic range
- Duty cycle
- Auxiliary sensors



IMPACT cell





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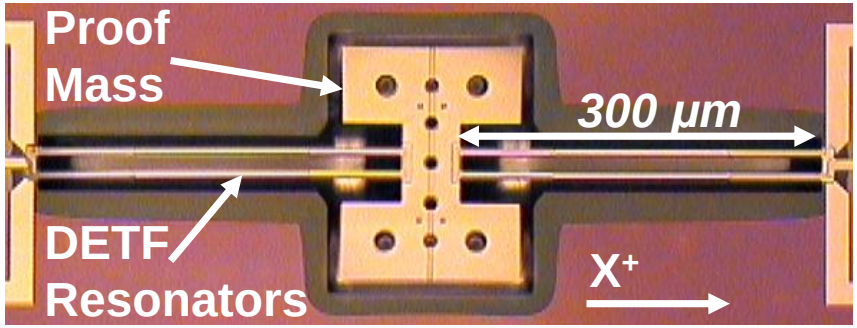
MEMS Inertial Sensors

Accelerometer Development

- Noise resolution ranging from:
  - 1.5 ng/Hz$^{1/2}$ with a 40 Hz resonator to
  - 0.9 mg/Hz$^{1/2}$ with an 800 kHz resonator compatible with CMOS integration.

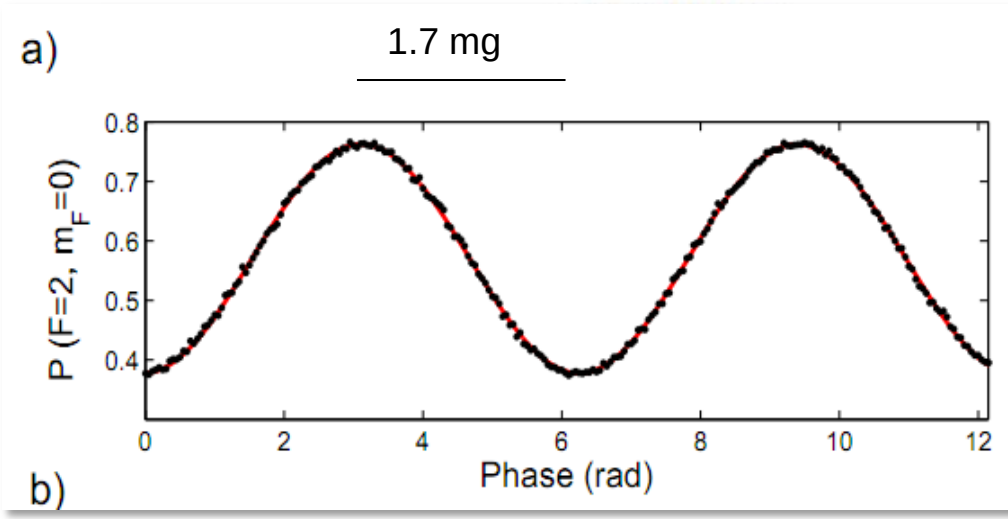
$$\delta a = \sqrt{\frac{4K_b T \omega_r}{QM}}$$



AlN Resonant Accelerometer Picture

Advantages of MEMS/AI Hybrid

- Atom interferometer strengths: excellent long-term stability, high accuracy
- Develop the MEMS sensor to bridge the gap between system requirements and AI capabilities.
- Bandwidth: AI: 50 Hz with dead time
  MEMS: 100 Hz-1 kHz with no dead time
- Limited dynamic range of AI
  - $\Delta\phi = a\, k\, T^2 \rightarrow$ 1.7 mg for $\Delta\phi = \pi$, $T = 3.4$ ms
- MEMS sensor can keep track of acceleration in high jerk environments to maintain lock to a fringe



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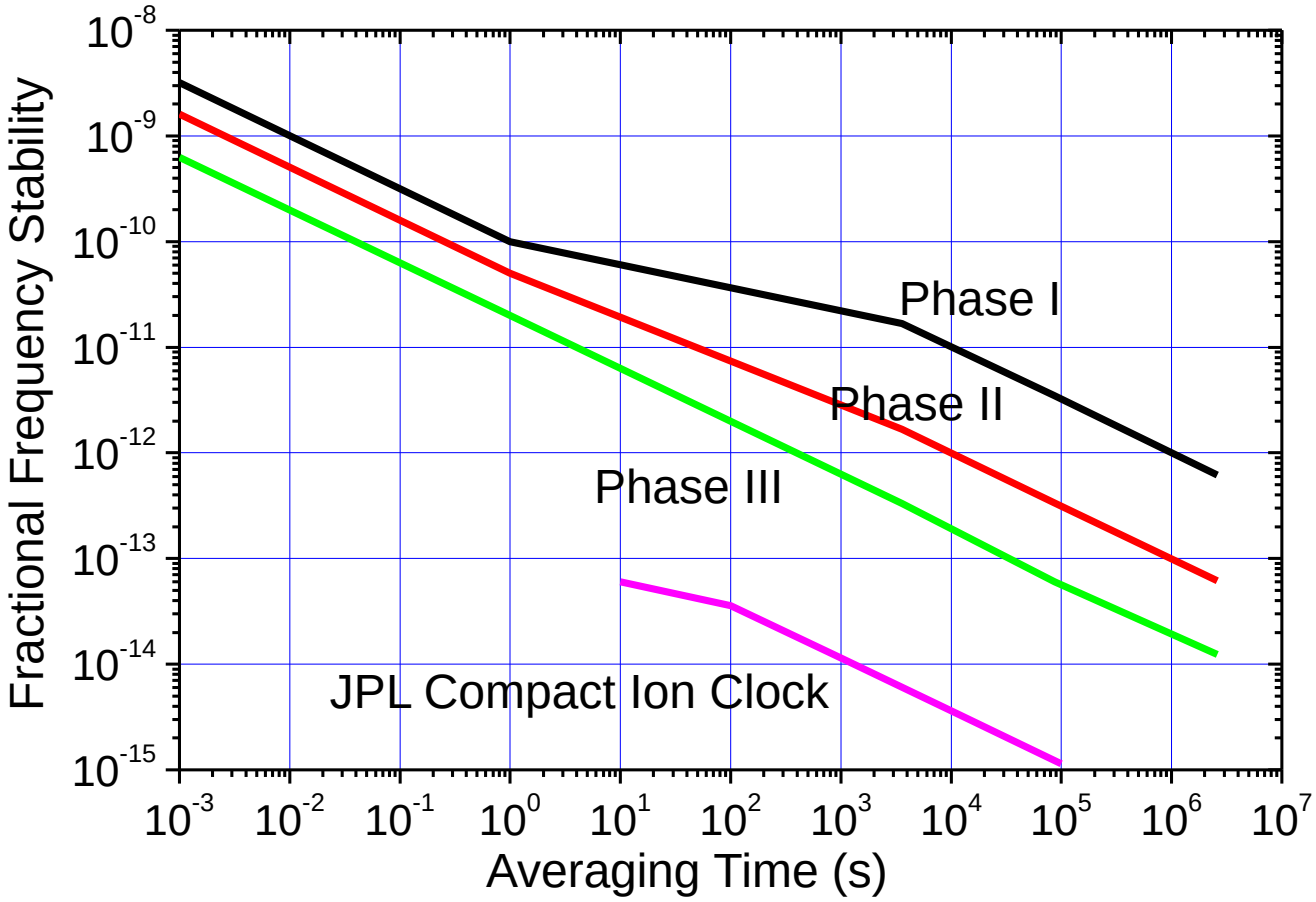
IMPACT Goals



Power = 50 mW

Size = 5 cm3

Fractional Frequency = 1.0×10^{-13} Retrace

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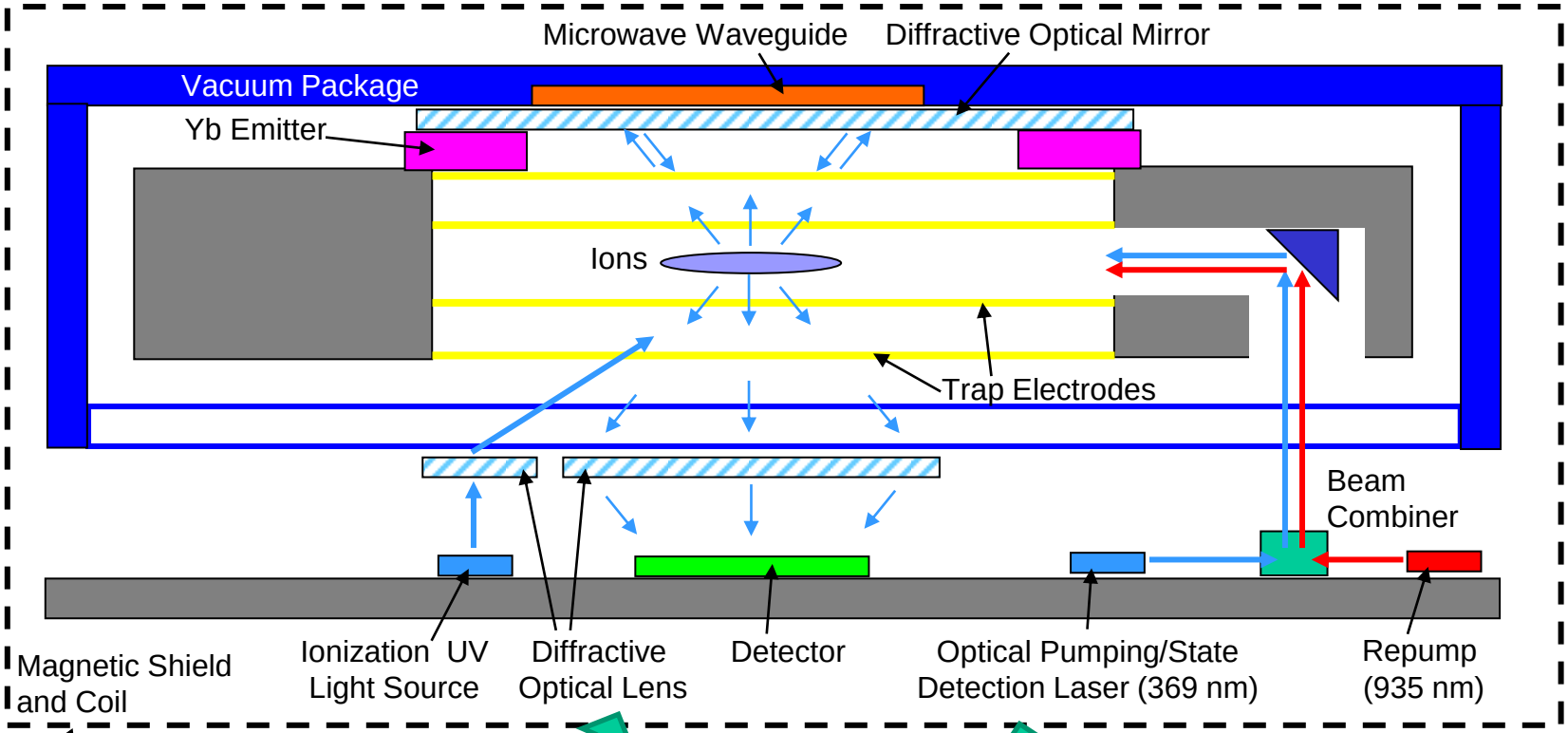
Critical Elements of the $^{171}Yb^{+}$ Clock



Physics Package including optics and vacuum packages

Control and Power Electronics

Local Oscillator

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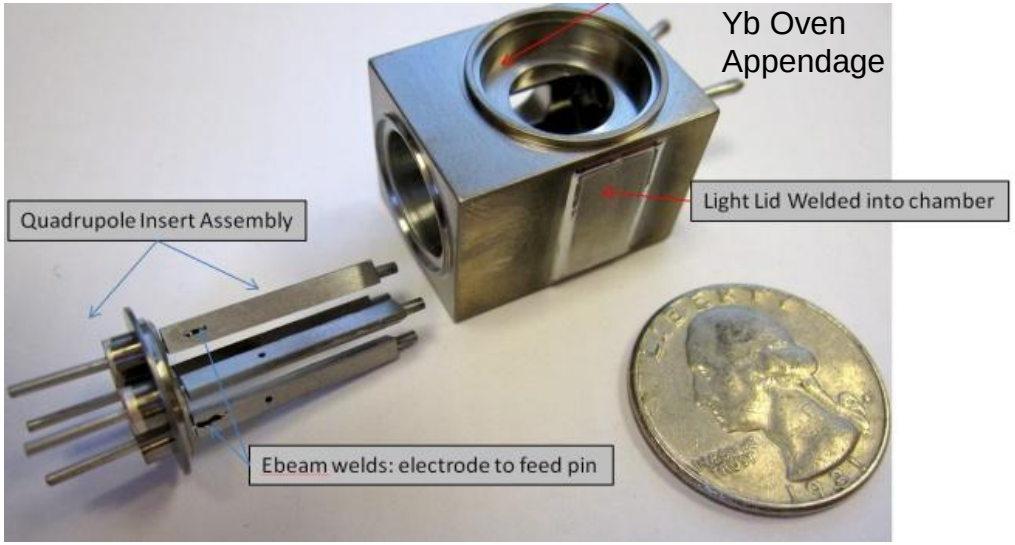
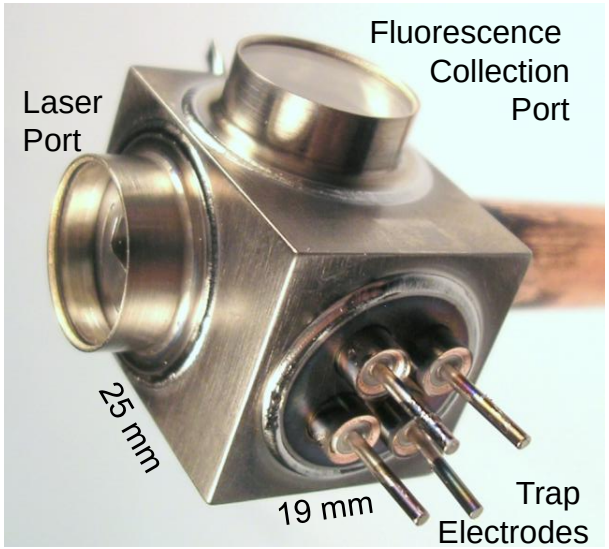
IMPACT Phase I
Vacuum Package

- Designed, fabricated, two 10 cm^3 vacuum physics packages
  - Requirements include use of non-magnetic materials and high temperature bake.
    - Titanium body, sapphire windows, molybdenum trap rods, copper pinch-off tube.
  - Fabricated via in-vacuum welding/brazing.
  - 400 C bake/de-gassing of tube carried out several times.
  - No active pumping, getter used.
    - Valved off since mid-January. Pinched off since April 4th.
    - Trapped ion lifetime > 500 hours.





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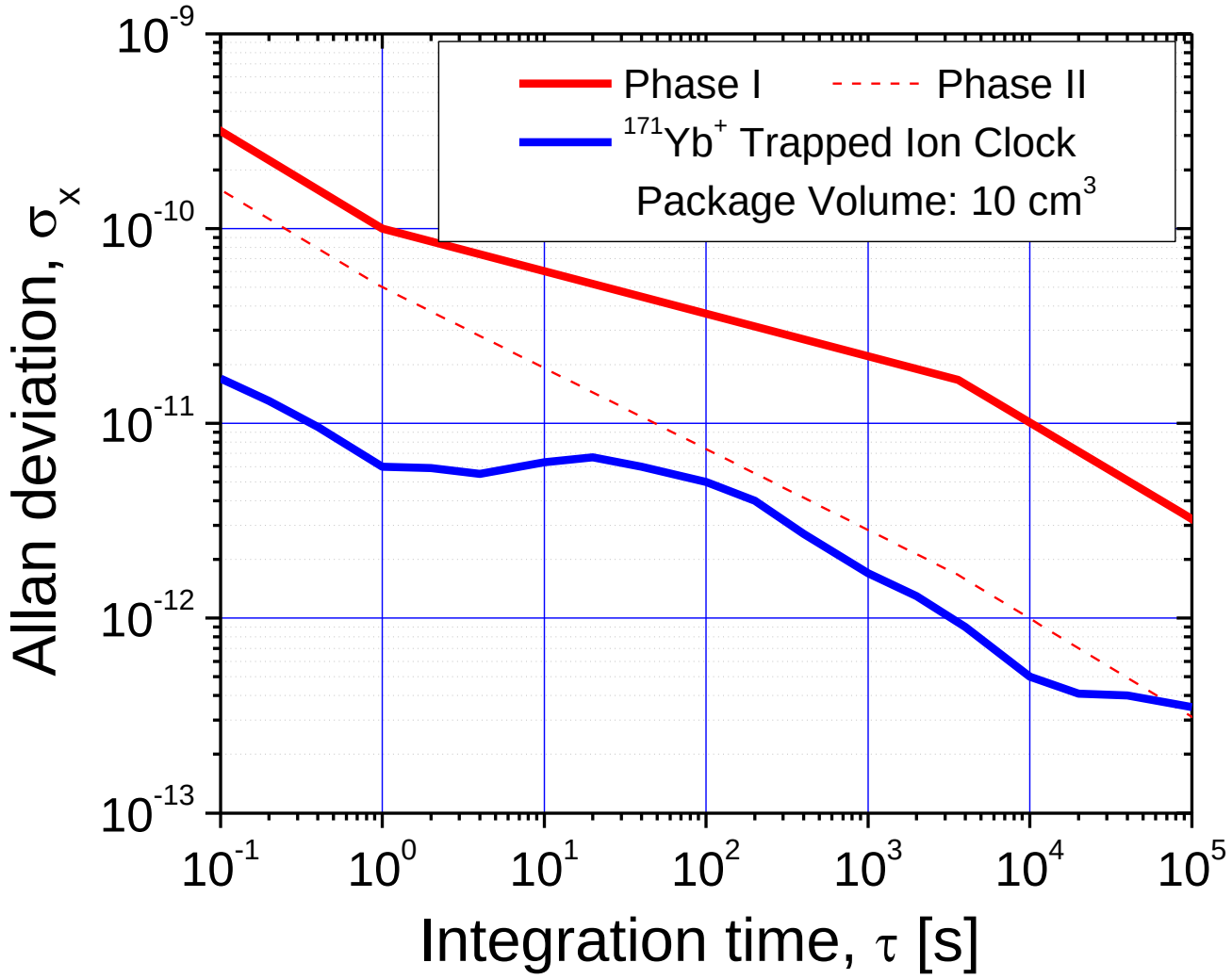
Performance of the 10 cm^3 Vacuum Package



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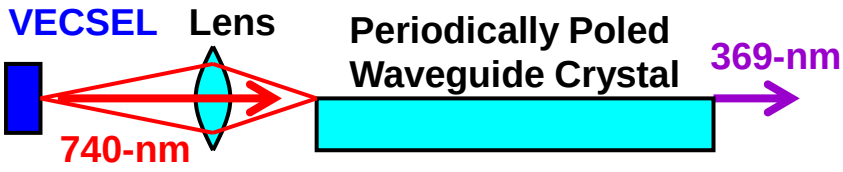
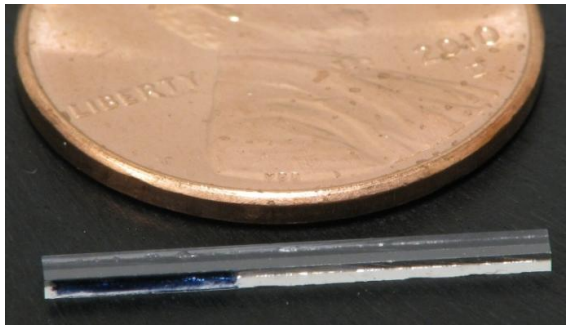
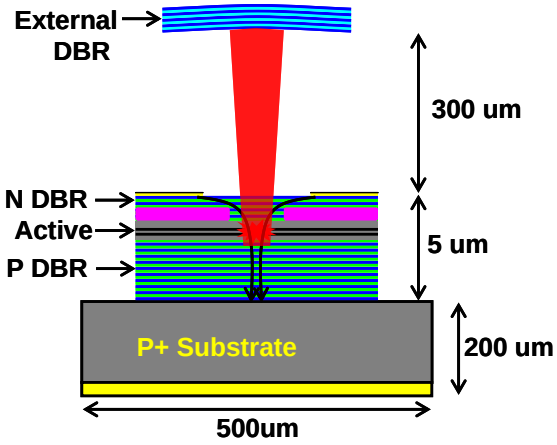
369 nm Light Source

- Vertical External Cavity Surface Emitting Laser (VECSEL) at 739 nm
  - High output power due to larger gain area
  - Narrow linewidth
- Double with a PP KTP or lithium tantalate waveguide crystal
  - Waveguide confinement gives large intensity for efficient conversion

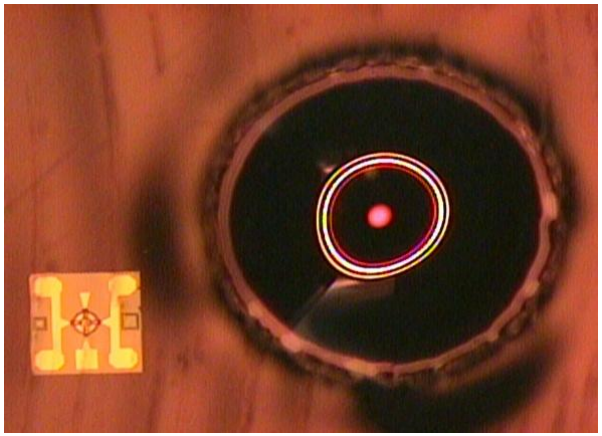




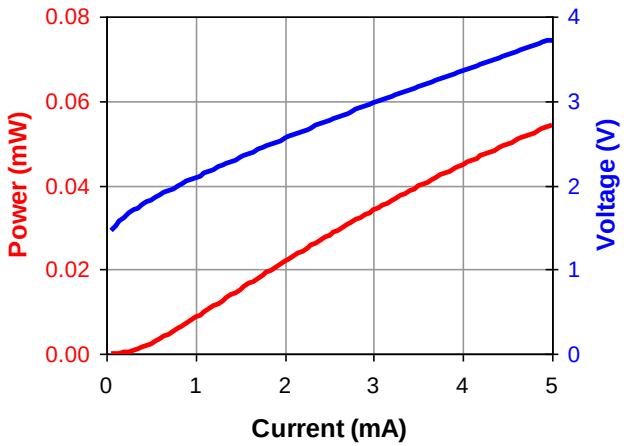
Assemble VECSEL



External Mirror & Gain Chip



740nm RC-LED LIV



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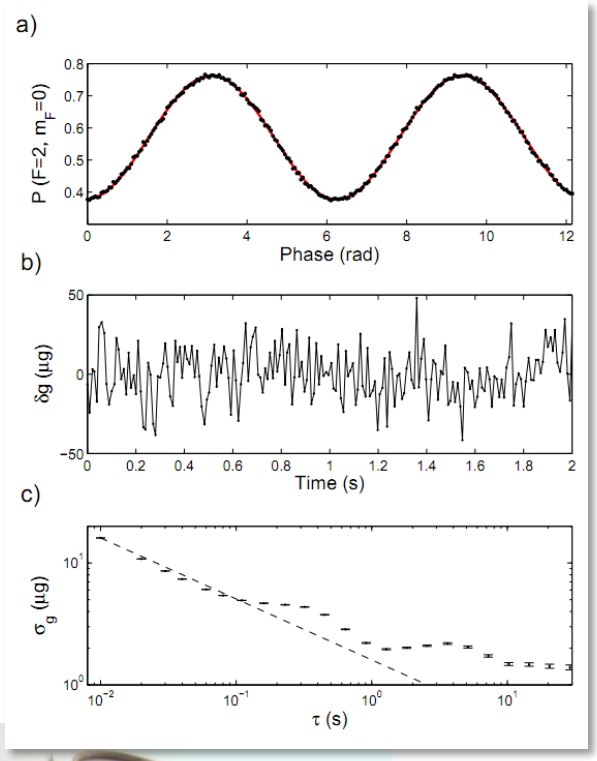
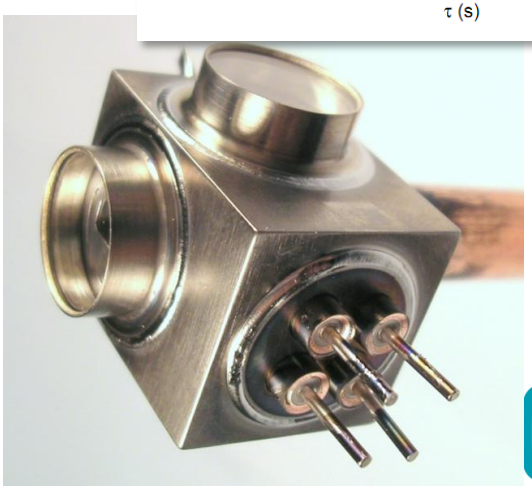
Conclusion

- Demonstrated a high data-rate atom interferometer
  - 1.6 μg/Hz$^{1/2}$
  - 100 Hz data rate
- MEMS sensors can augment atom sensor in high jerk and high bandwidth applications (fast turn-on)
- IMPACT technologies point the way for miniaturizing AI devices





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