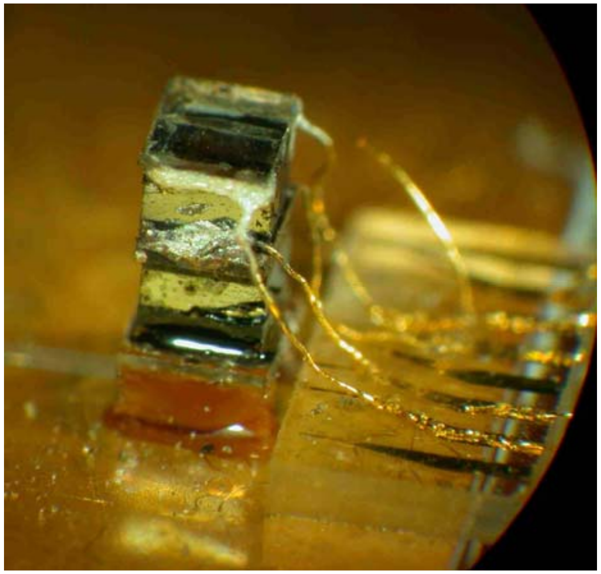
Chip-Scale Atomic Devices



John Kitching

Time and Frequency Division

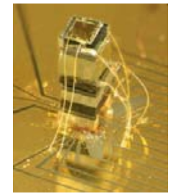
National Institute of Standards and Technology

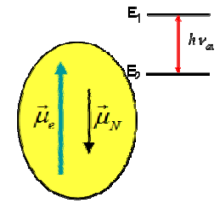
USA

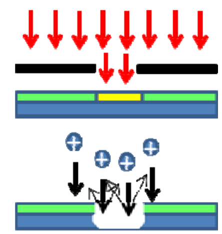
National Institute of Standards and Technology

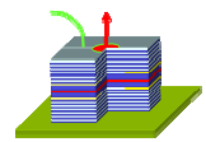
Atomic Devices and Instrumentation Group

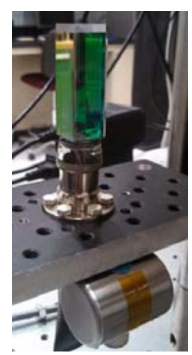
- Formed in 2009 based on success of chip-scale atomic clock program
  - CSACs largely unique when program began at NIST
  - Now many groups doing similar things (Switzerland, France, UK, China, Japan)
- Applied research into practical devices
  - Spectroscopy + MEMS + diode lasers
- Current activities
  - Chip-scale atomic magnetometry (Svenja Knappe)
  - Compact cold atom systems (Liz Donley)
  - NIST on a Chip (me)
- Outcomes
  - Regular scientific publications and talks
  - Six patents
  - Many collaborations with industry (Honeywell, Texas Instruments, Geometrics, Quspin, ColdQuanta, Symmetricom, Tristan, HRL, Analog Devices, Vixar, Princeton Optronics…)

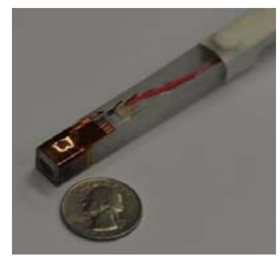


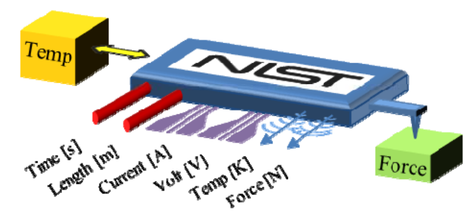






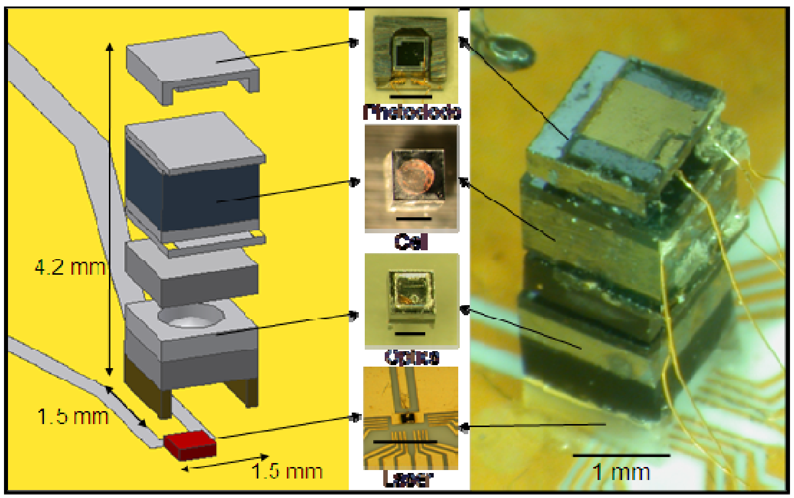


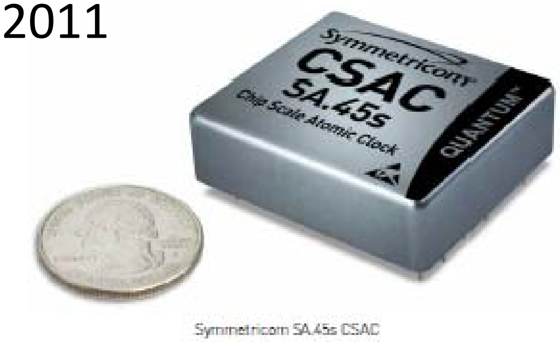


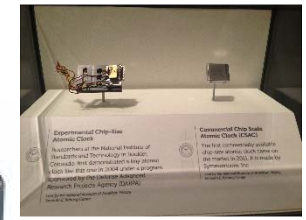


Chip-Scale Atomic Clocks

- DARPA-funded program ran 2002 – 2009 + 3 years ManTech
  - Early development pioneered at NIST
  - Commercial product as of January, 2011

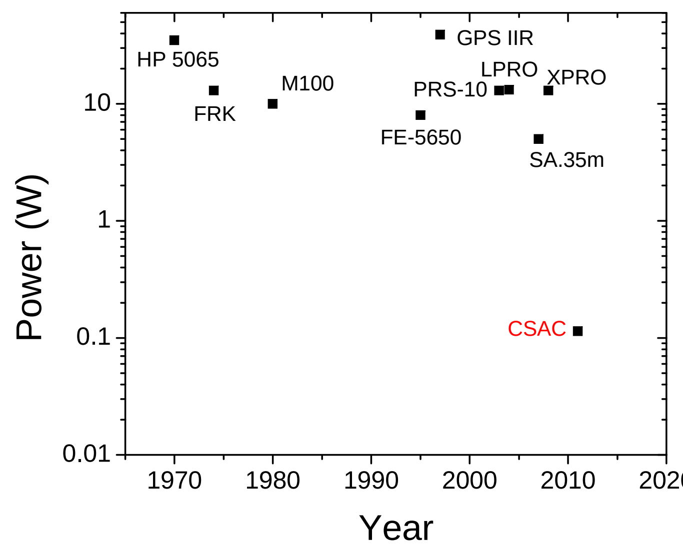






Smithsonian Air and Space Museum

Leo Hollberg



<u>DARPA CSAC goals/achieved</u>

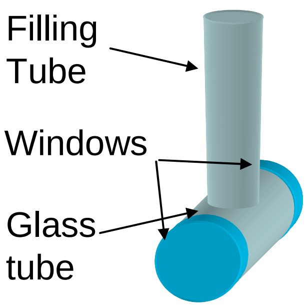
- 1 cm^3 / 10 cm^3
- 30 mW / 120 mW
- $\Delta f/f = 10^{-11}$ @ 1 hour

<u>Army ManTech goals</u>

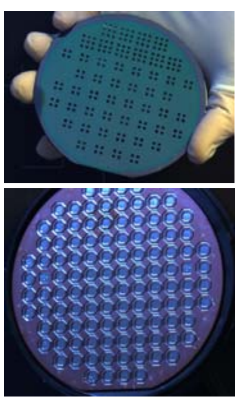
- $100 / unit
- 20,000 units/year

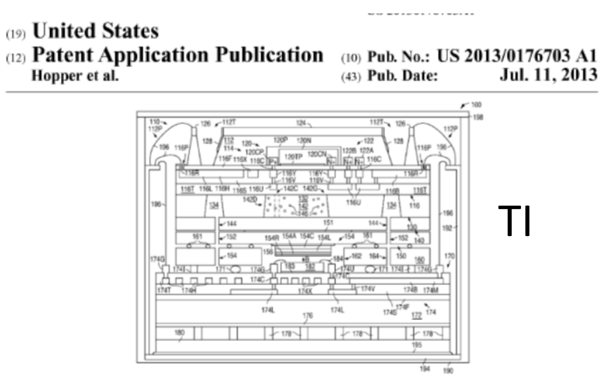
Alkali Vapor Cell Fabrication using MEMS

Conventional Cells



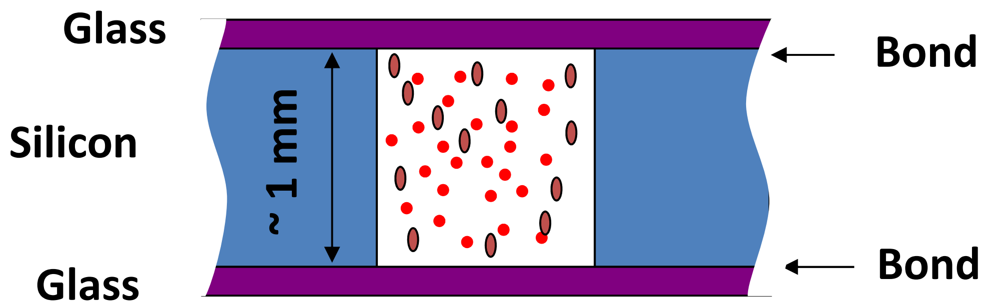
- Large; long relaxation times
- Buffer gases or wall coatings
- Good optical access for perpendicular pump/probe

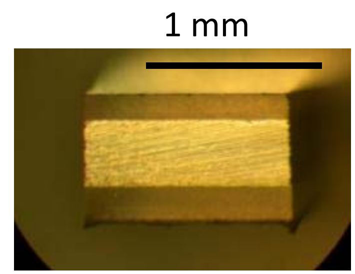


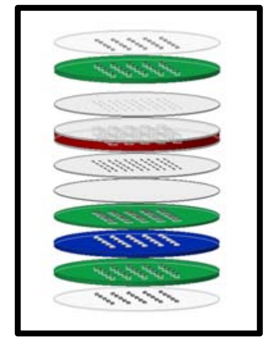

(19) United States
(12) Patent Application Publication
Hopper et al.
(10) Pub. No.: US 2013/0176703 A1
(43) Pub. Date: Jul. 11, 2013

TI

Microfabricated Cells

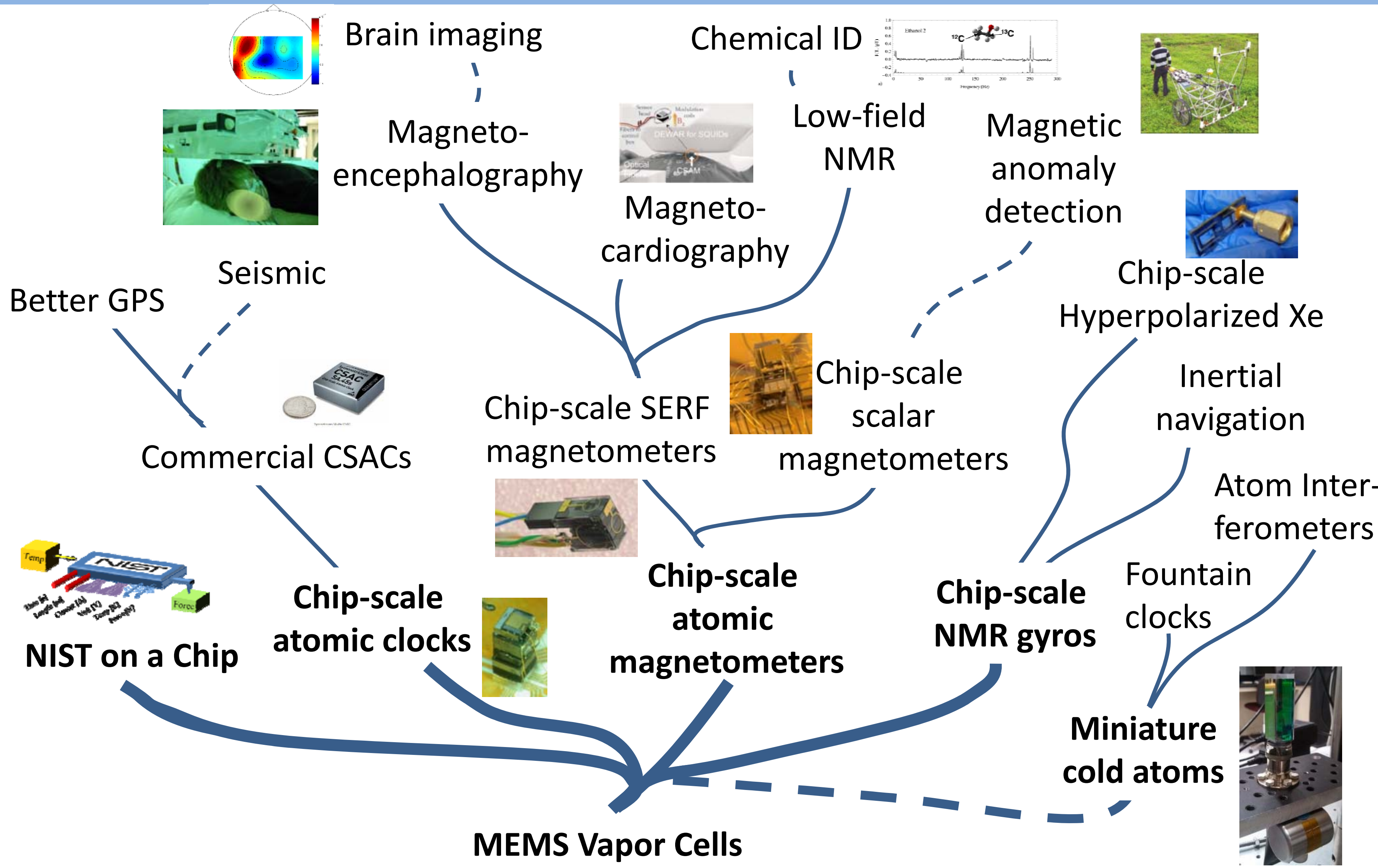




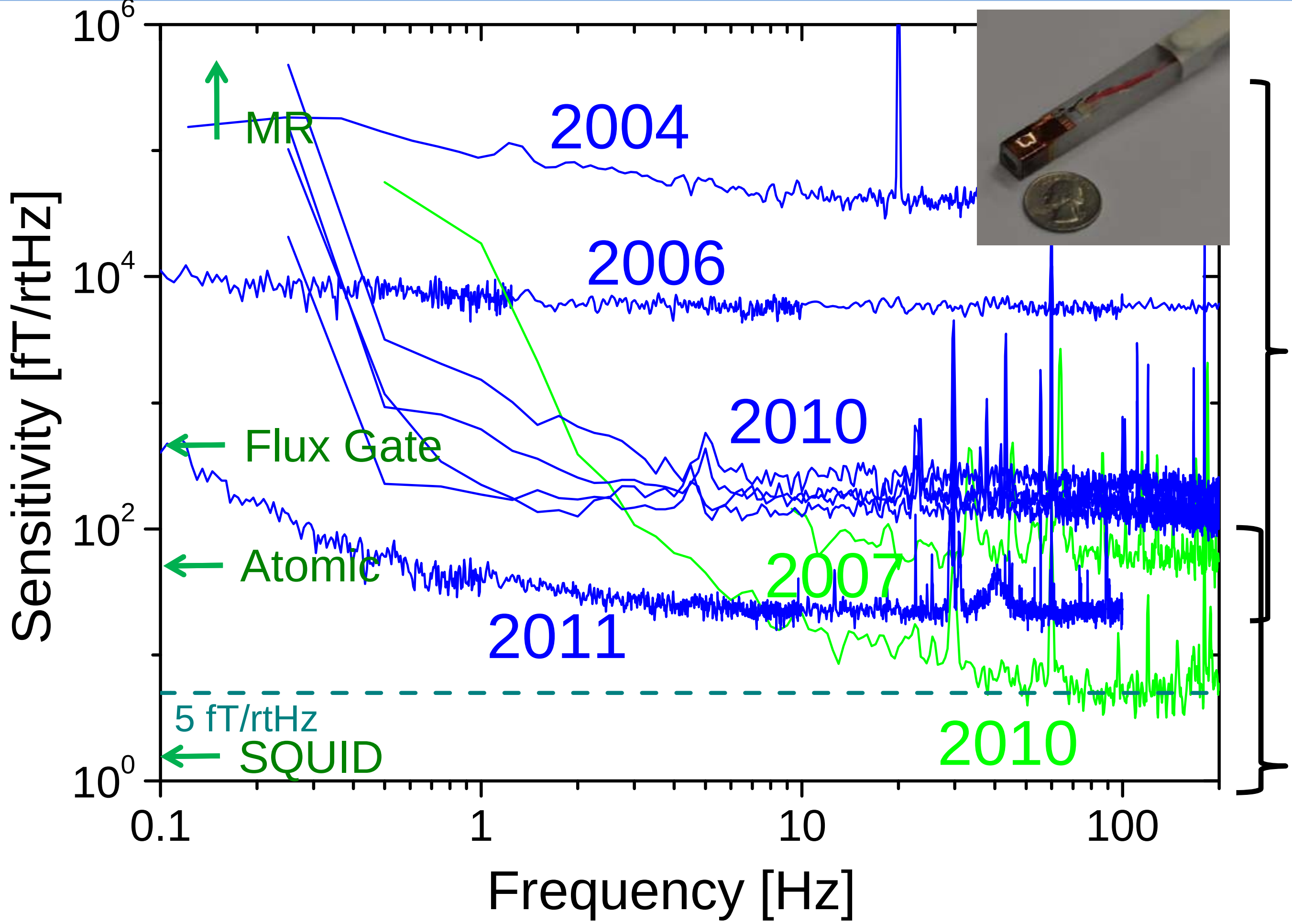


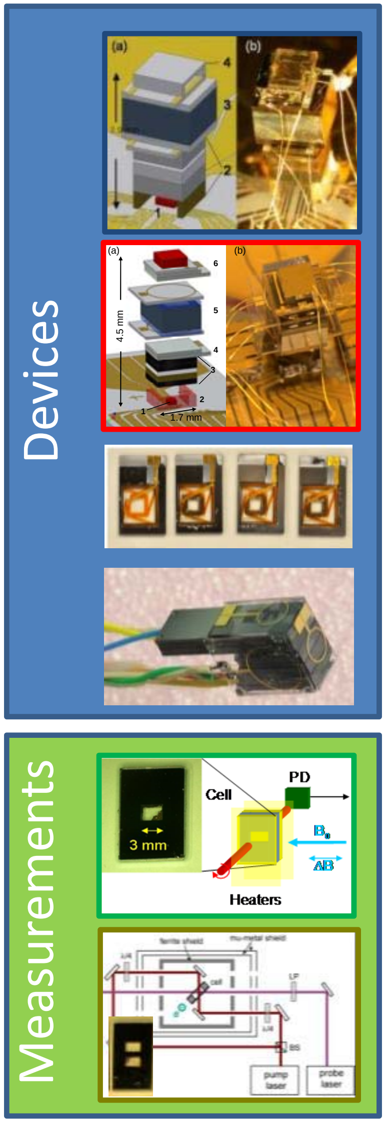
- Small, scalable, easy to integrated
- Enables low-power instruments (chip-scale atomic clock)
- Parallel fabrication for low-cost mass-production

Technology Evolution



Chip-scale Atomic Magnetometers





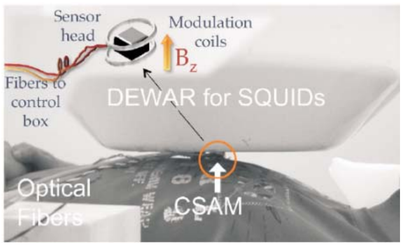
No cryogenics, small size, low power, low cost

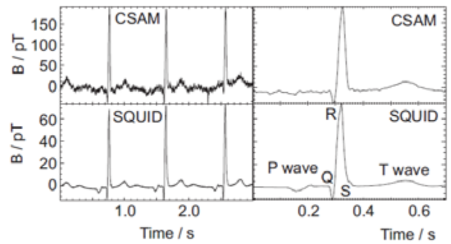
Magnetometer applications

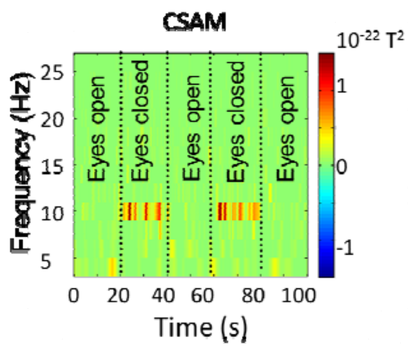
Biomagnetics

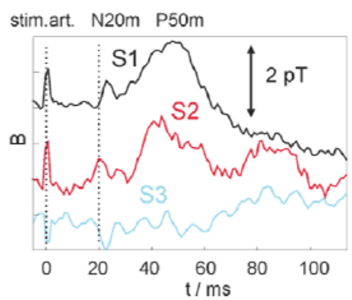
Svenja Knappe

- Heart and brain signals: low frequencies (0.1 -100 Hz), very weak (1 pT – 100 pT)





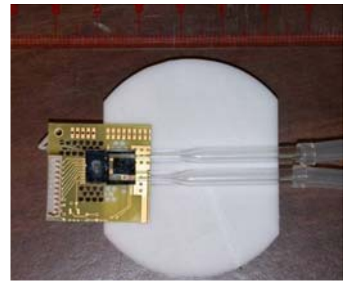


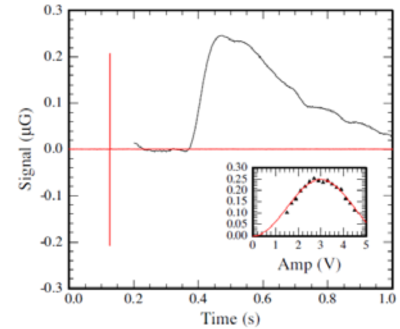


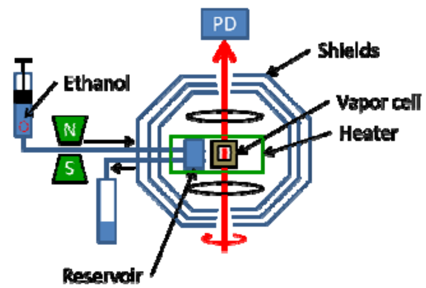
With L. Trahms, T. Sander, PTB

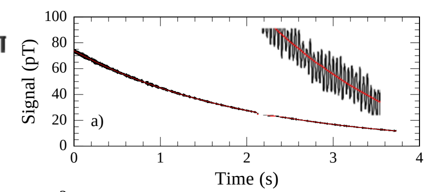
Low and zero-field NMR

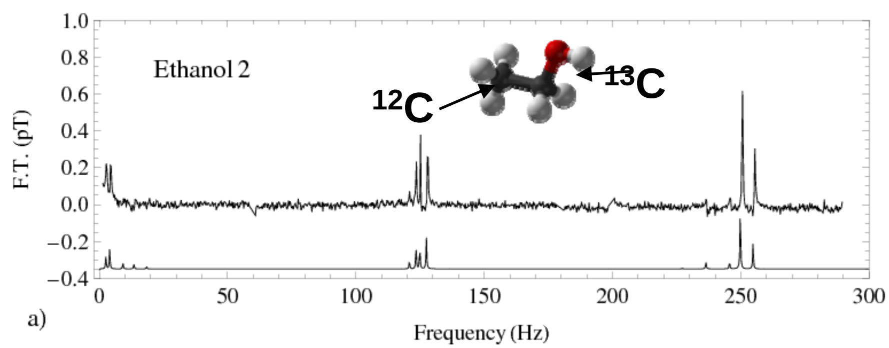
- With A. Pines, D. Budker, UC Berkeley





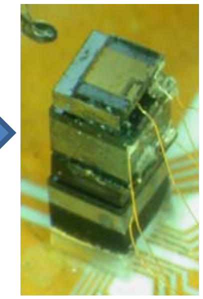


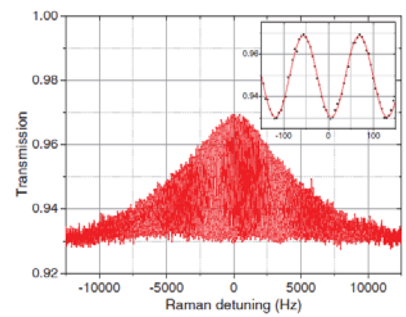


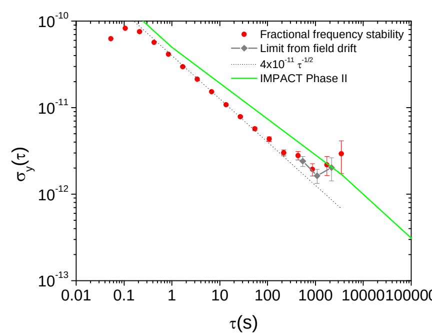


Miniaturized Laser Cooled Systems

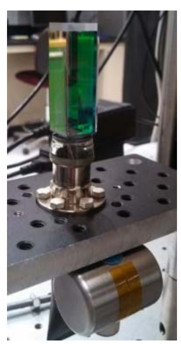
- Laser cooling allows microkelvin temperatures, slower atom velocities and better performance
- Current generation of primary frequency standards at NIST (NIST-F1, NIST-F2) are based on laser cooled atoms
- Our group: liter-size physics packages with 10^{-12} frequency stability
- Accuracy of 10^{-13} possible

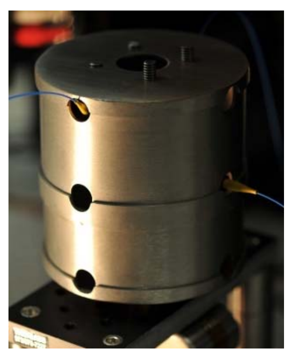






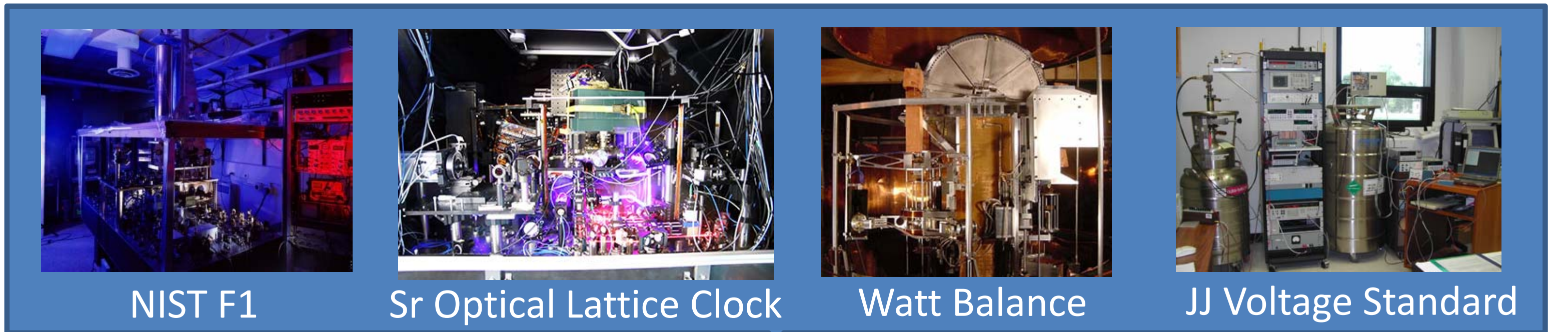
Liz Donley

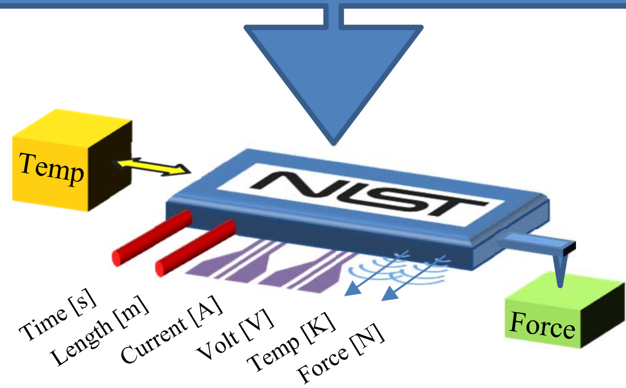




NIST on a Chip

- Measurement standards in chip format



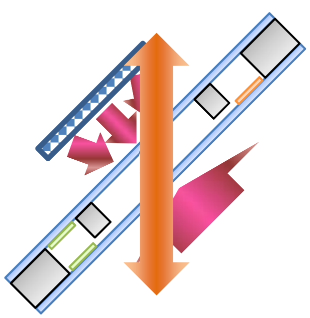


- Goals: SI-traceable, manufacturable, low-cost
- Get rid of the middle-man (NIST!)

NIST on a Chip with Alkali Vapor Cells

Time

- Cold neutral atoms on a chip
  - Passively pumped MEMS cell
  - Grating MOT
  - (Stimulated emission cooling)
  - $\Delta f \sim 10^{-10}$

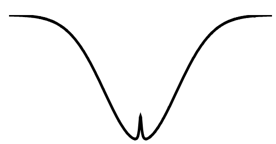


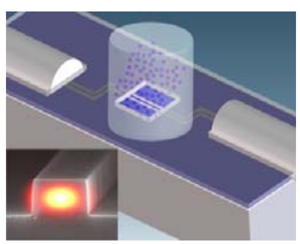
- Chip-scale Cs beam clocks?

With Liz Donley

Length

- Integration of vapor cells and single-mode photonics
  - Lamb dip, 2-hv ?
  - $\Delta f \sim 10^{-9}$
  - Atomic cladding waveguides

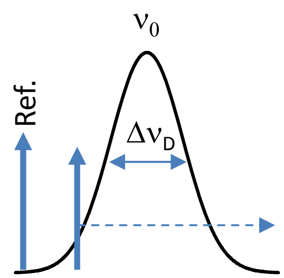




With Kartik Srinivasan, Vladimir Aksyuk, Uriel Levy, Matt Hummon others

Temperature

- Doppler thermometry
  - Measure Doppler-broadened lines spectroscopically
  - $k_B T = \frac{mc^2}{2}\left(\frac{\Delta\nu_D}{\nu_0}\right)^2$
  - Current expt's achieving ~ 10^{-5} accuracy → 10^{-6}

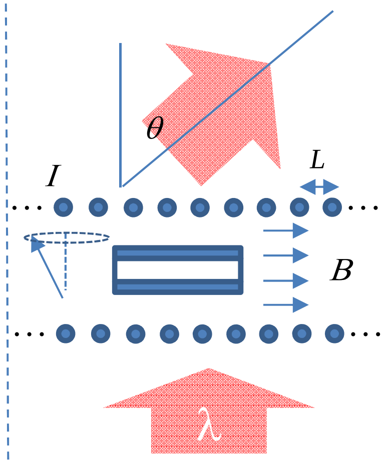


See: Borde (2005), Daussy (2007), Truong (2011)

Current

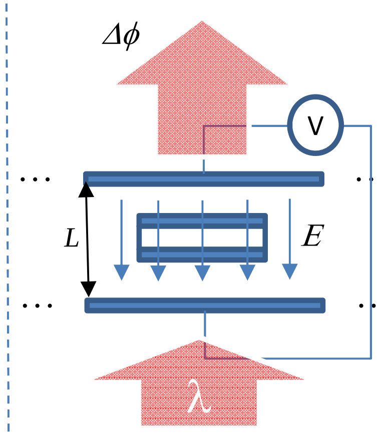
- Larmor prec.

  Many g-factors known to ~ 10^{-8}
  - $\frac{f_L}{\gamma} = B = \frac{\mu_0 I}{2L}$



Voltage

- DC Stark shifts
  - Rydberg atoms for large polarizability
  - $h\Delta f_S = -\frac{\alpha_0}{2}\left(\frac{V}{L}\right)^2$
  - For Yb, $\delta(\alpha_0) \sim 10^{-5}$



With Jeff Sherman

4+1 of 7 base SI units could be realized at chip-scale with microfabricated alkali vapor cells

Summary

- Clocks, magnetometers, gyros, accelerometers, etc.
  - All based on cutting edge science of ~ 30 years ago
  - Reinvented with MEMS and lasers
- Focus on applied science, innovative instrumentation and technology transfer
  - We are trying earnestly and directly to improve US technology and manufacturing by developing new instruments and technology that can be used in the real world
  - We have reinvented ourselves several times over: clocks -> magnetometers -> gyros -> brain imaging -> photonics
- Much still to be done

NIST
National Institute of Standards and Technology