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Development of (Miniaturized) Trapped Yb Ion Clocks

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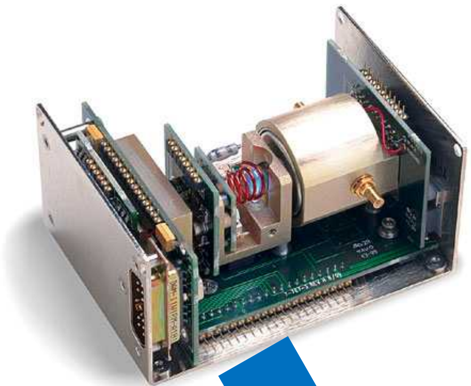
Outline

- Introduction
  - Why trapped ions for miniaturization?
- Miniaturized vacuum package: 1 cm^3
  - Pulsed-mode ion clock performance
- F-state trapping
- Current focus: microwave optical double resonance continuous operation
- Alternative ion clock: Alkali Mediated Atomic Clock
- Conclusion

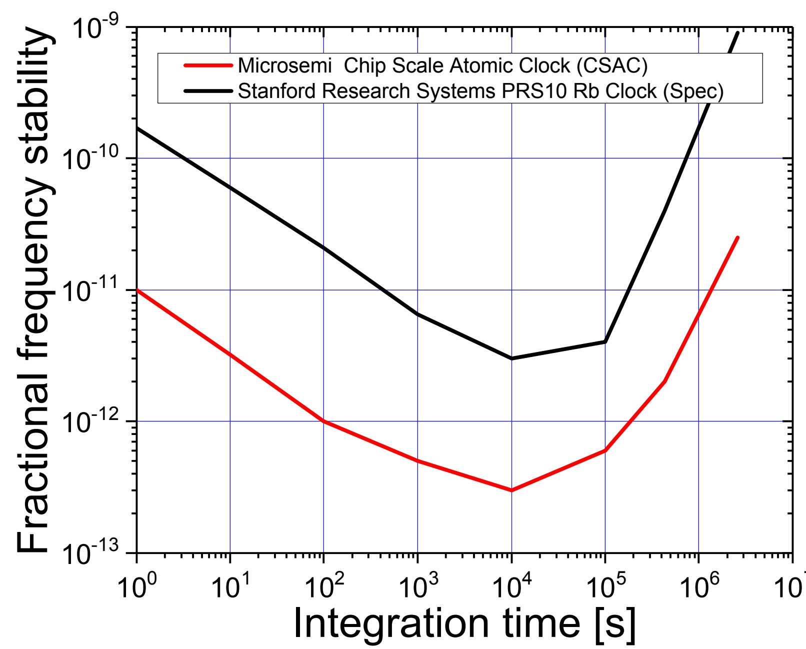
Atomic Clock Miniaturization

- Rubidium Vapor Cell Clocks
  - Excellent for miniaturization
  - Relatively poor long-term stability



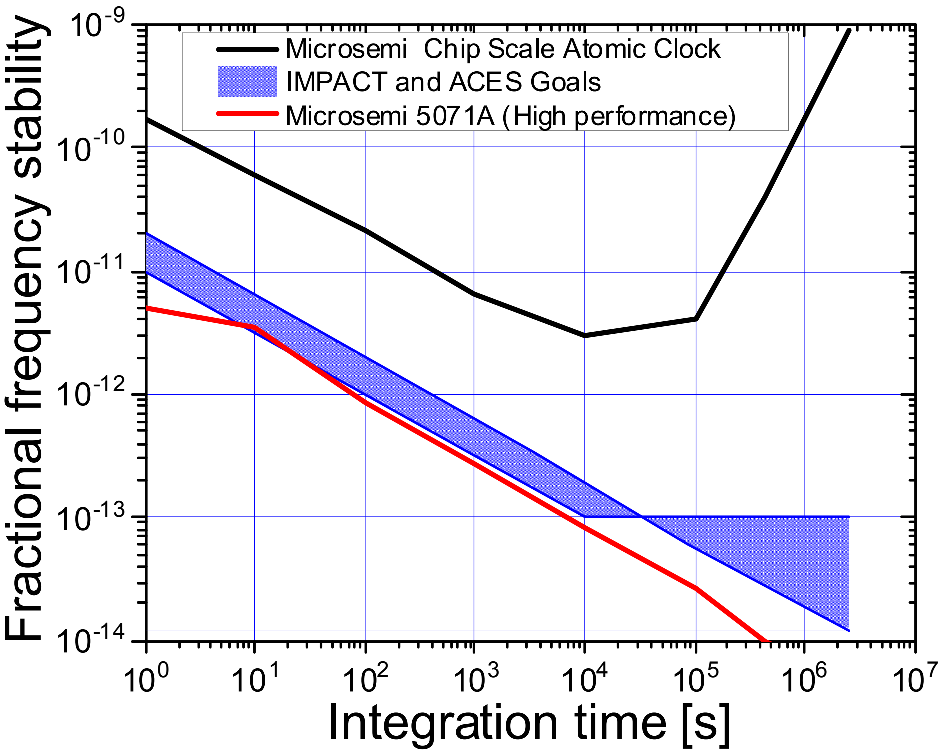
PRS10 Rb Clock
Lamp pumped
Power: 14 W
Size: 262 cm^3

Microsemi CSAC
Laser pumped
Power: 0.12 W
Size: 17 cm^3



Miniaturization with Long-Term and Environmental Stability

- Achieve Cs Beam Clock performance in a mass and power constrained package
- DARPA programs:
- IMPACT: improved long-term stability
- ACES: improved environmental stability



Applications--Excellent timing for:

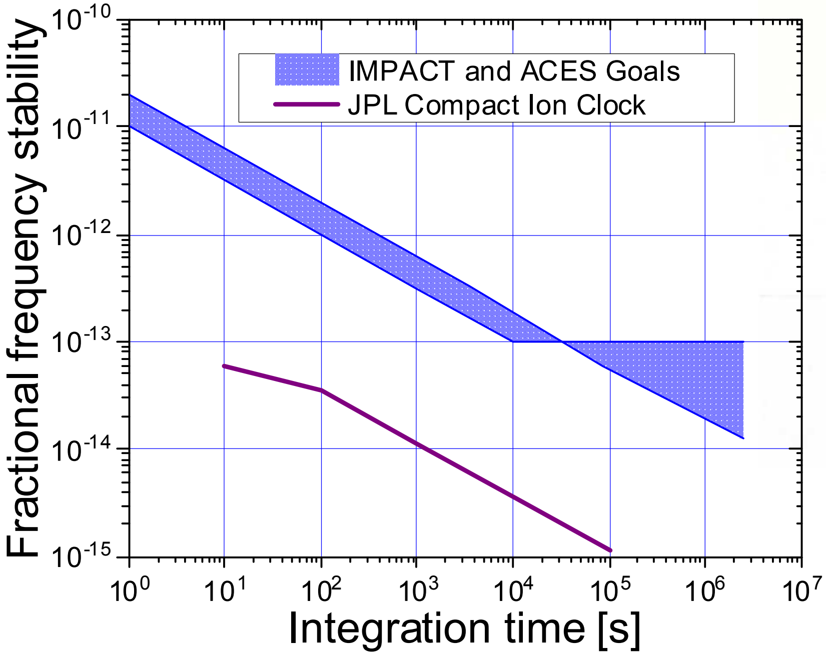
- Rapid GPS acquisition, and GPS denied navigation and timing
- Nano/pico (cube) satellites
- Pulsed radio and spread spectrum communications

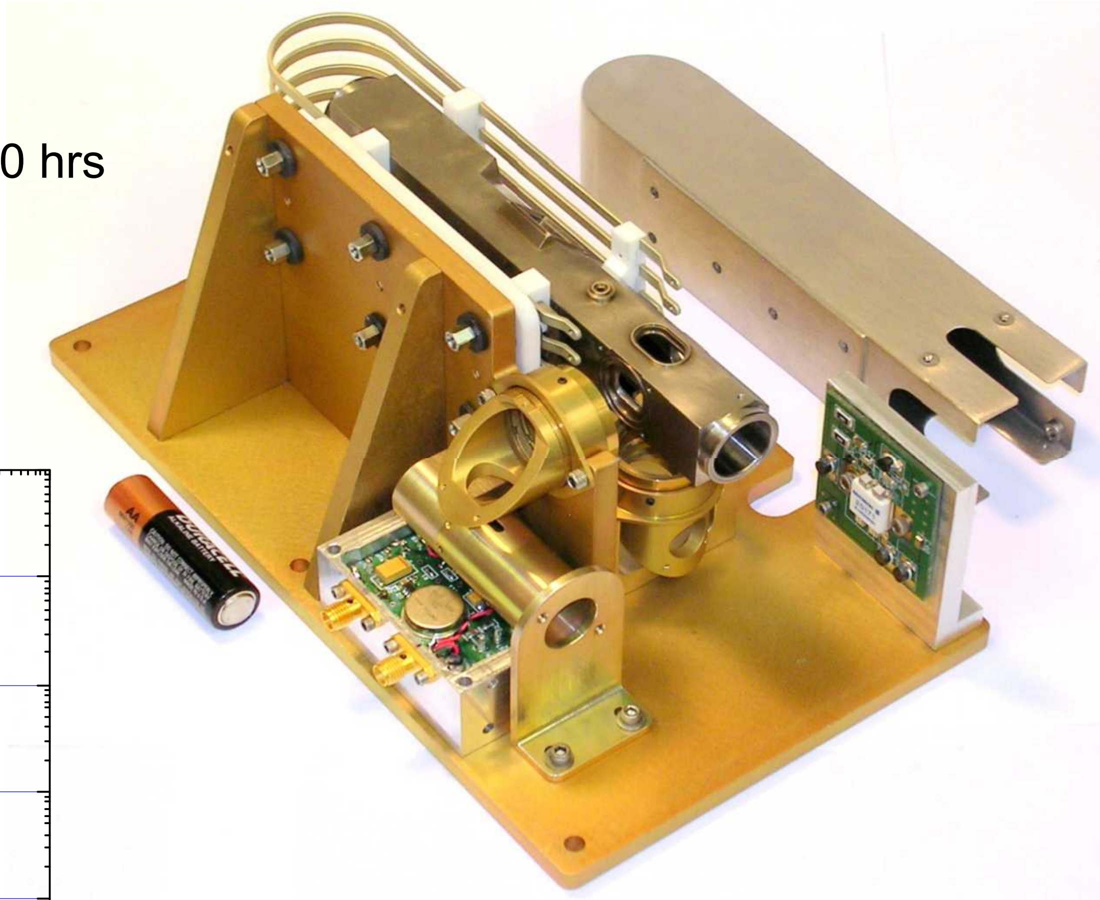
Microsemi 5071A

Miniature primary frequency standard

Trapped Ion Clock for Miniaturization

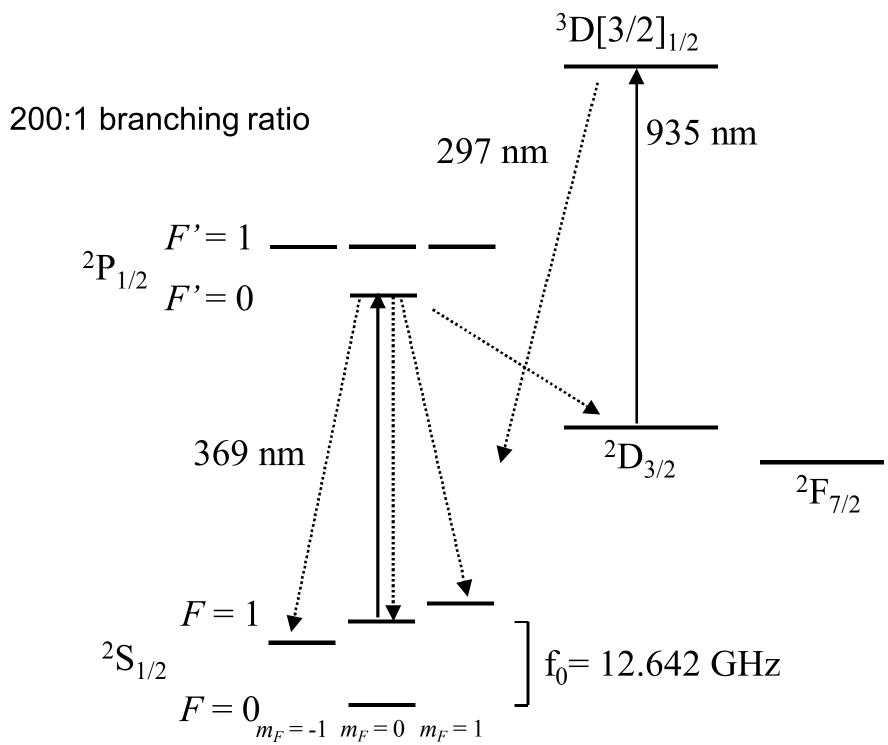
- Trapped ion clocks are already compact while delivering excellent performance.
- Low mass, size, power
- Trapped ion lifetime: up to 10,000 hrs
- Coherence time: > 100s
- Other approaches:
  - Miniature fountain clock
  - Miniature optical clock

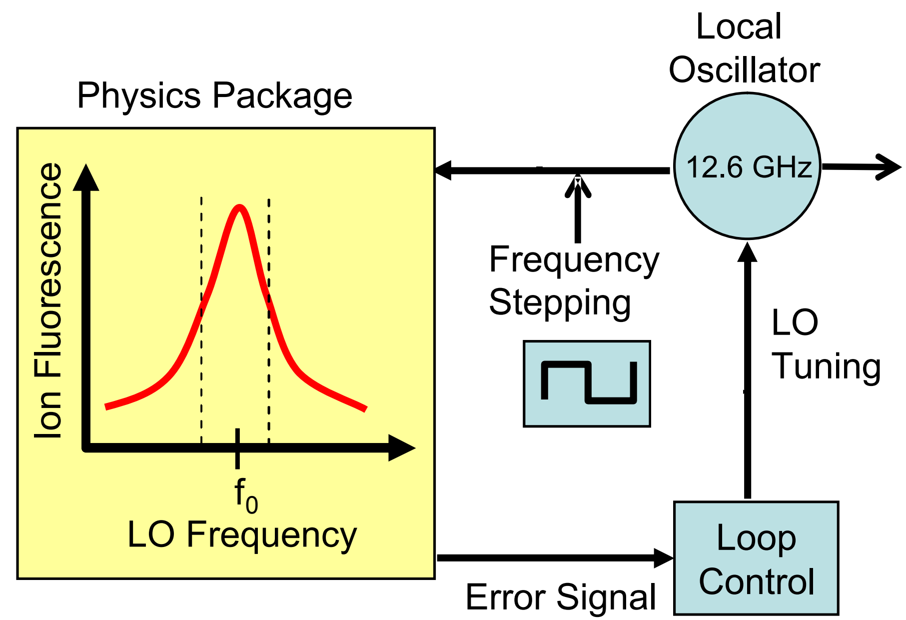


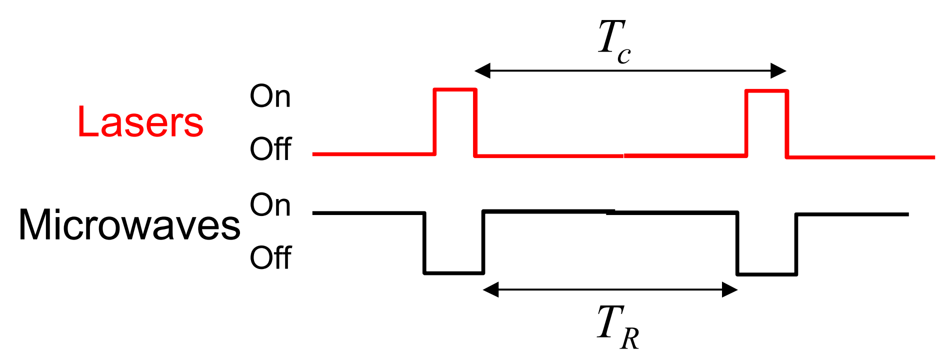


^{199}Hg Trapped Ion Clock from JPL

Atomic Frequency Reference with $^{171}Yb^+$







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

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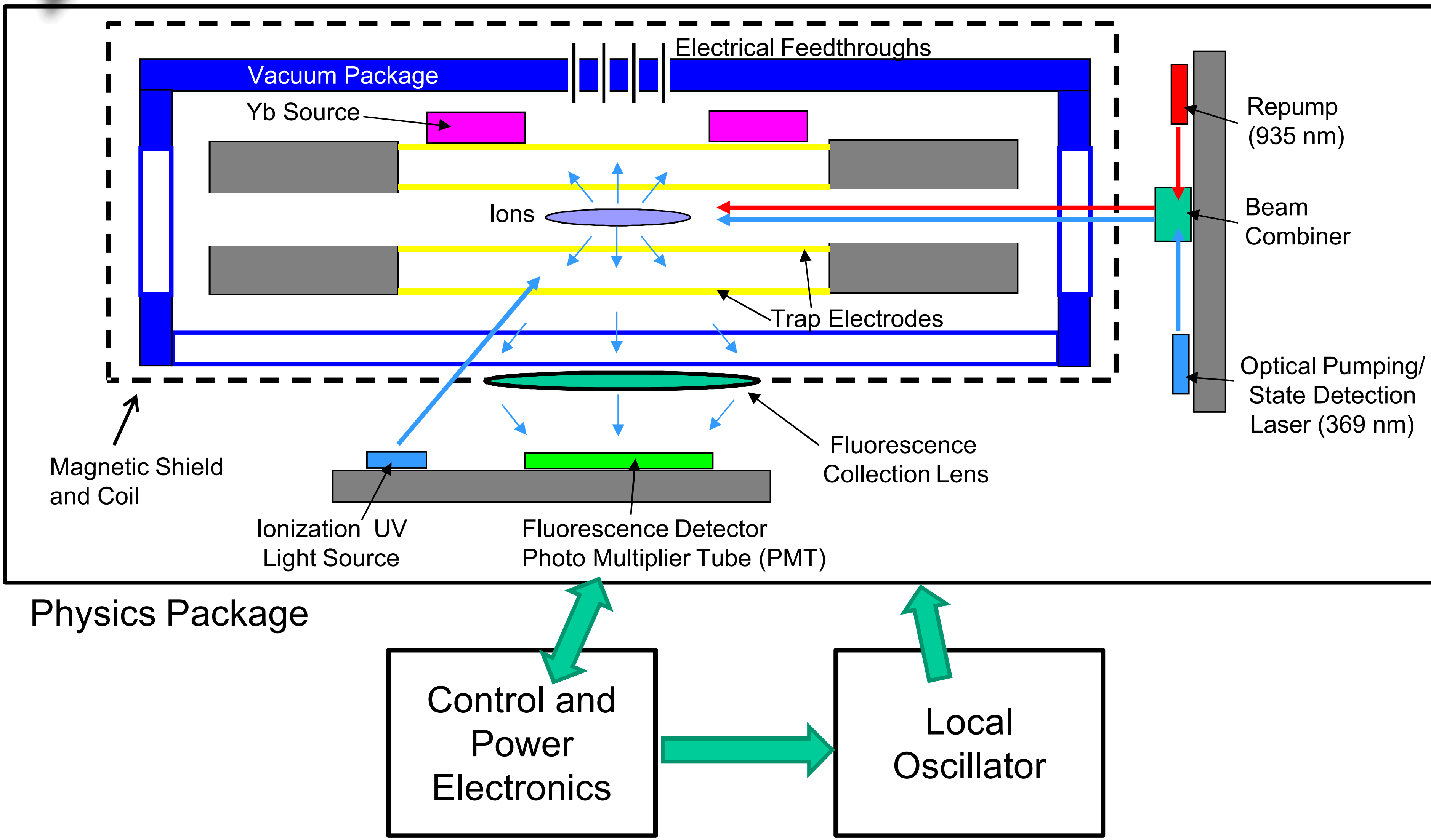
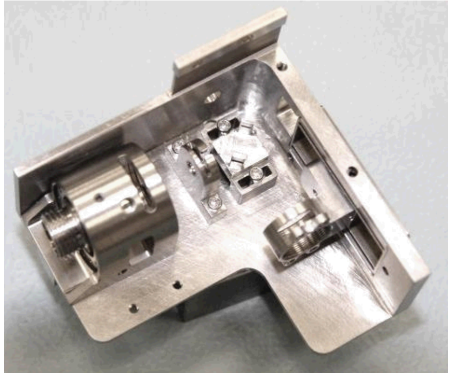
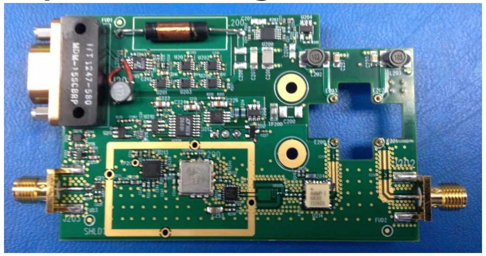


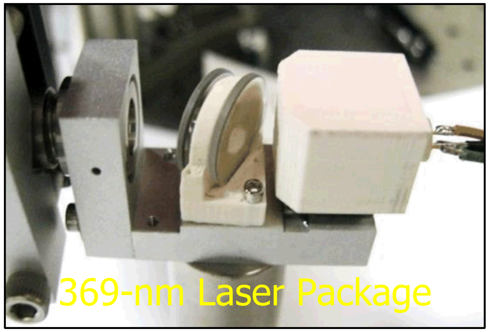
Complete Physics Package

Integrated Optics

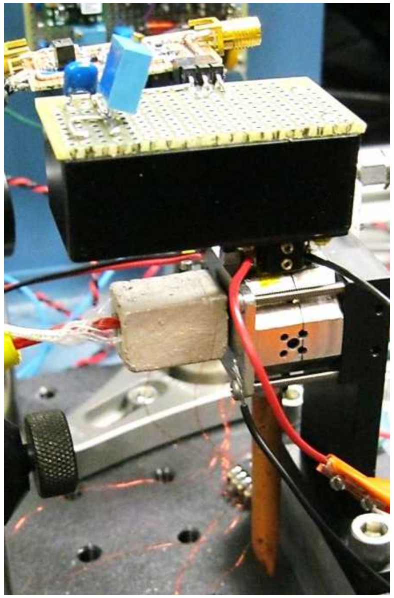


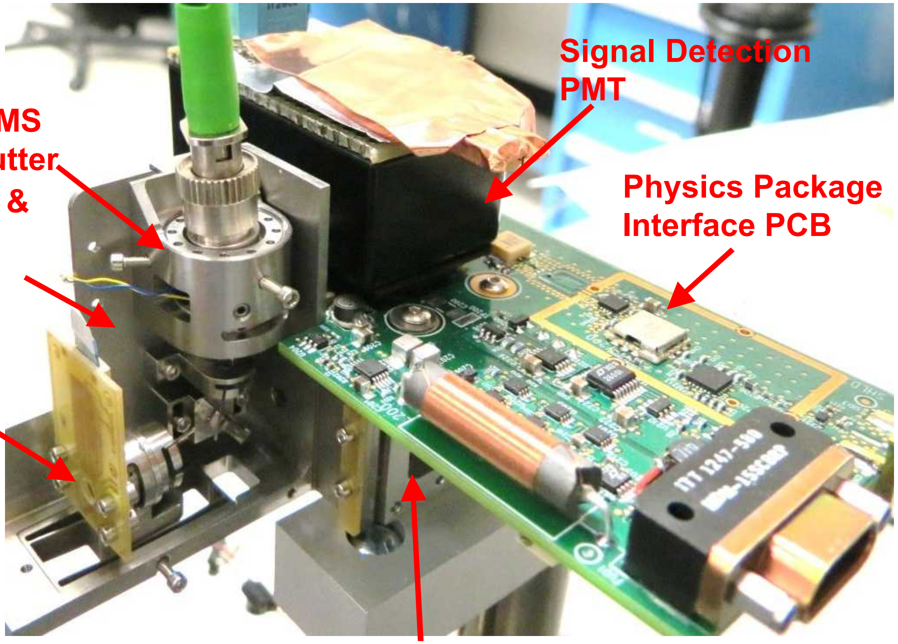
Physics Package Interface



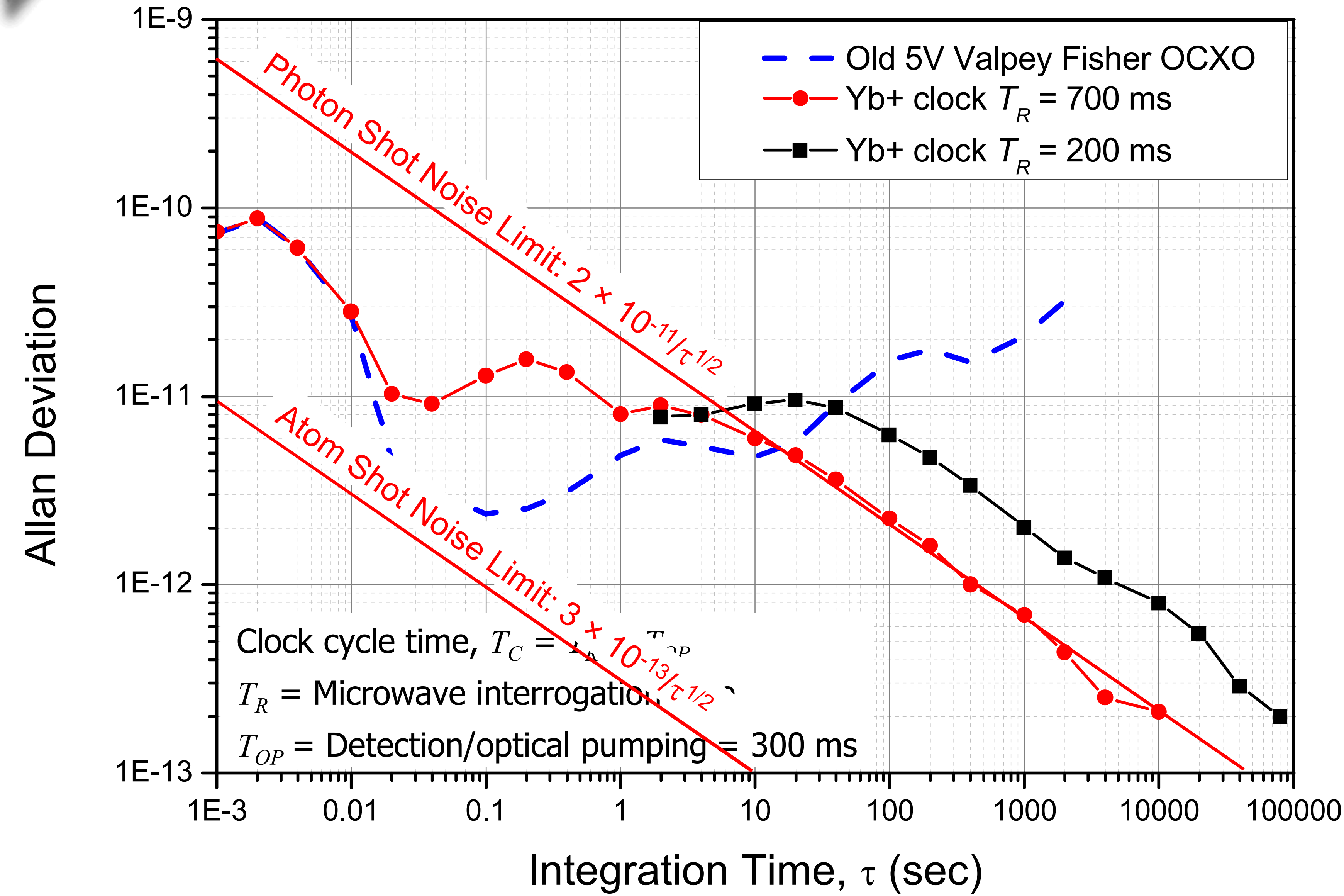


Vacuum Package





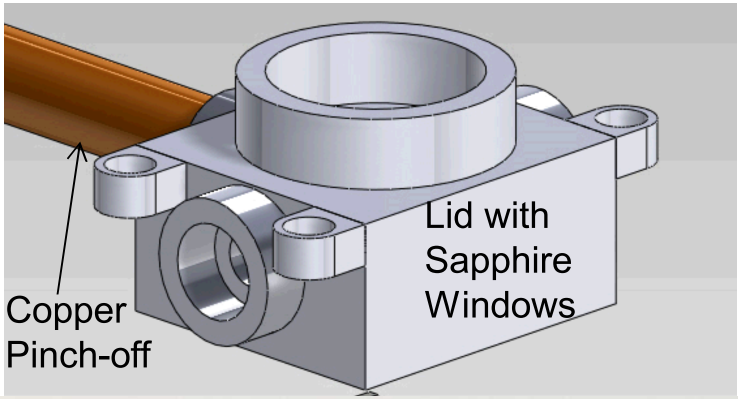
Integrated Clock Performance

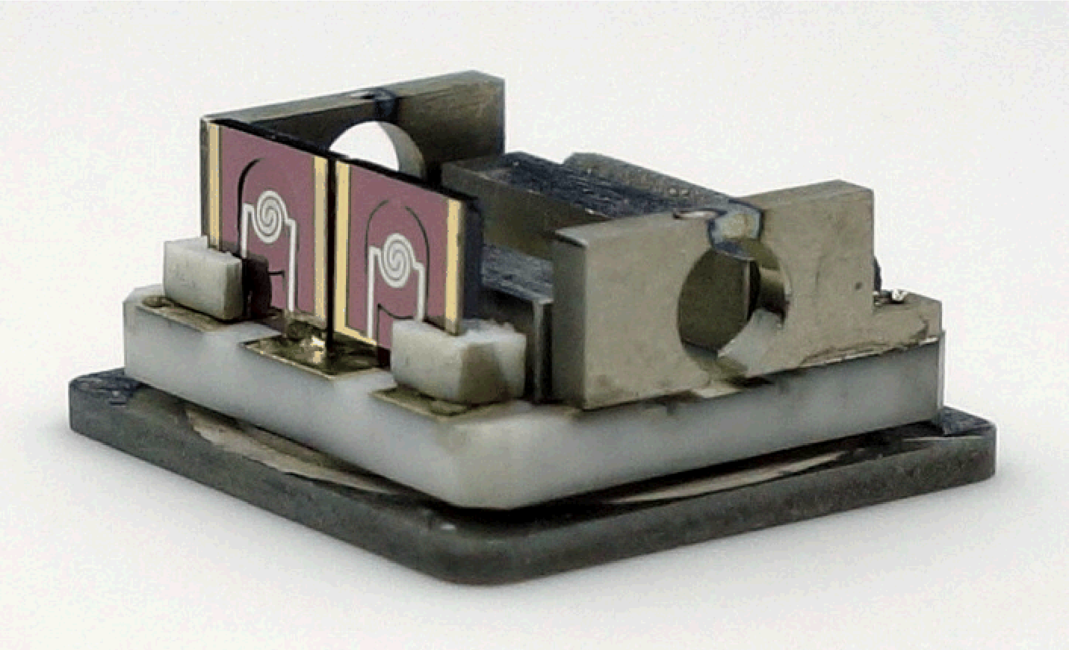


Co-Fired Hybrid Ceramic/Titanium Package

- High temperature co-fired ceramic (HTCC) simplifies the electrical vacuum feedthroughs and internal connections.
- Make the ion trap an integral part of the vacuum package for maximum miniaturization.
- Integrated Yb sources: Silicon micro hotplate
- CuAg braze the Ti parts to the HTCC
- AuGe solder Si hotplates to HTCC
- E-beam weld the base to the lid
- Size of package cube: 0.8 cm^3

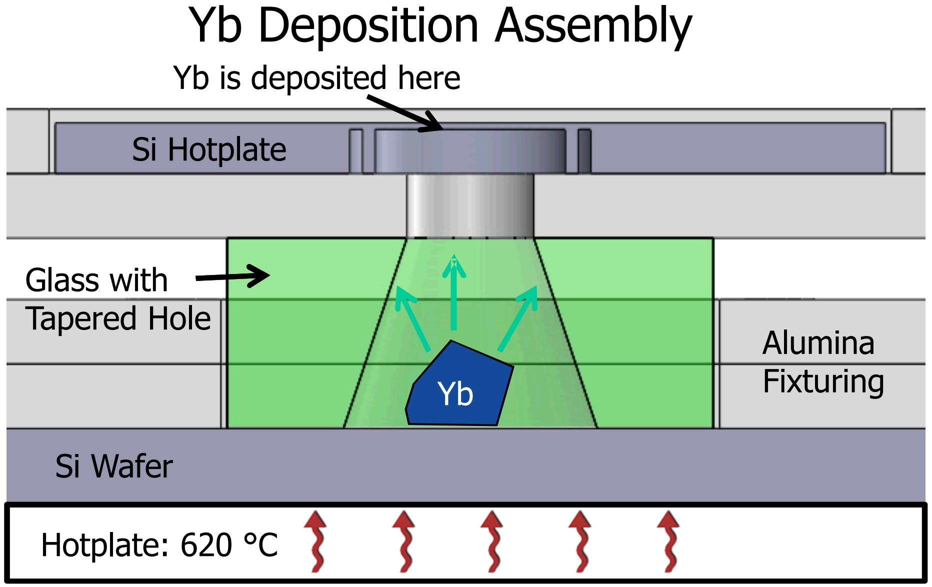
Exploded View

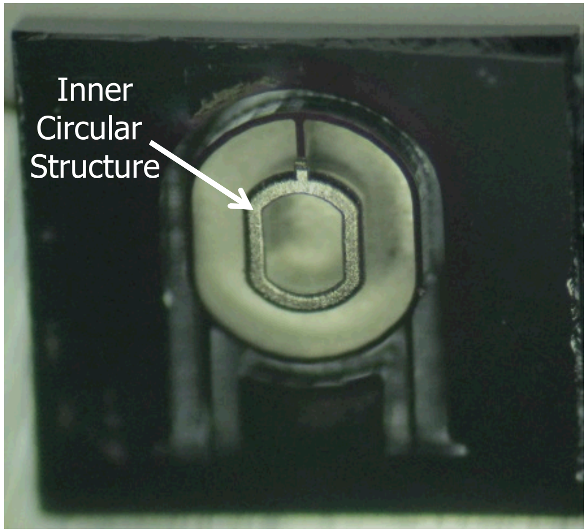


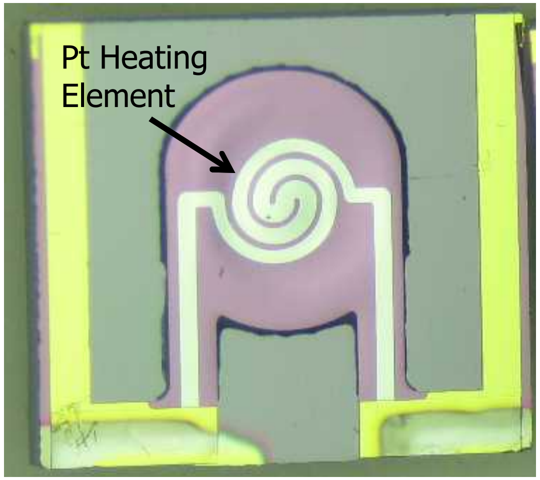


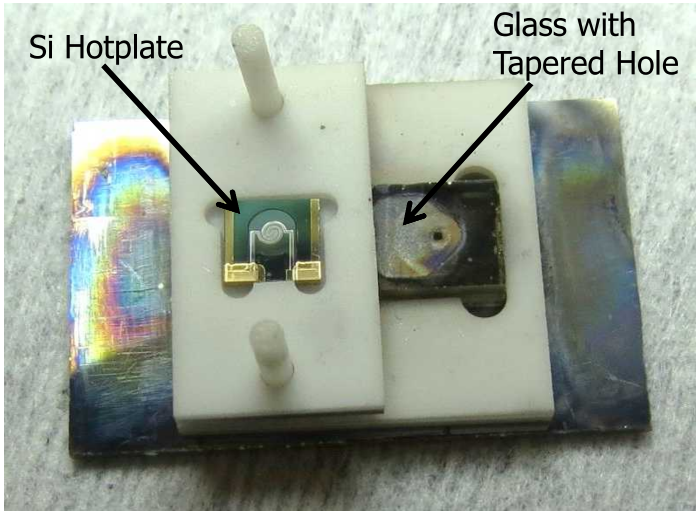
Yb sources: Silicon Micro Hotplate

- Evaporate Yb into the Si micro hotplates
- Heat base to 620 °C for 2 hours in vacuum
- 30-50% is deposited into the Si micro hotplate: 0.5-0.8 mg
- Inner circular structure in hotplate prevents CTE mismatch between Yb and Si from cracking the Si.
- Typical power for Yb evaporation: 1.5 V × 0.17 A = 255 mW









Performance of the Phase III Vacuum Package

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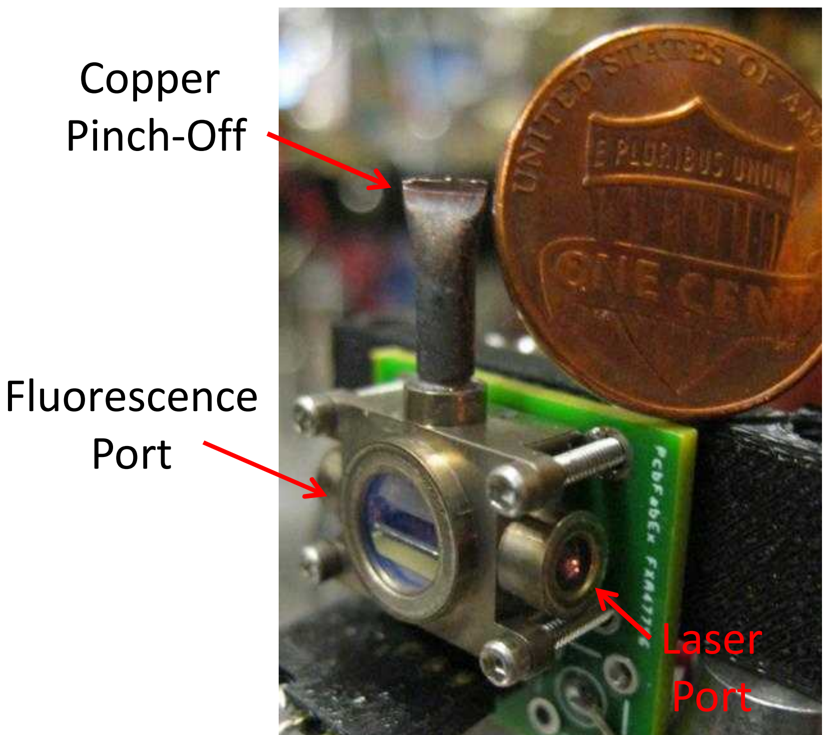
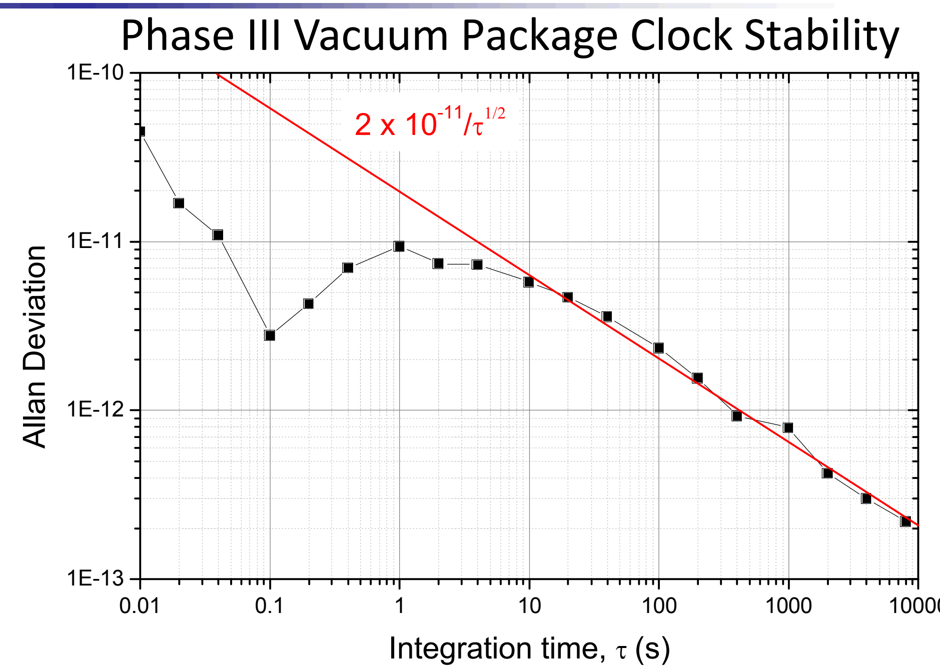
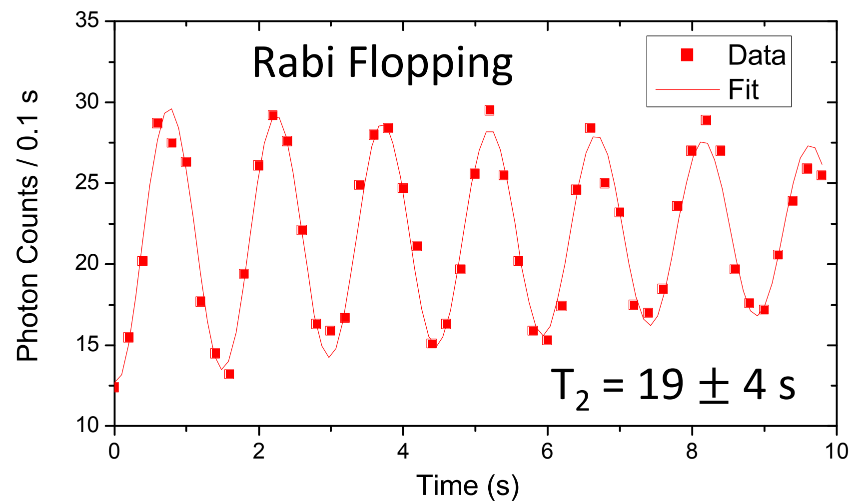
- The vacuum package was pinched-off on Thursday, October 30th, 2014.
- Trapped ion lifetime is ~50 hours.
- Achieving Phase III performance
  - $T_{microwave}$ = 700 ms
  - $T_{optical\ pumping}$ = 300 ms
- Magnetic field correlations removed

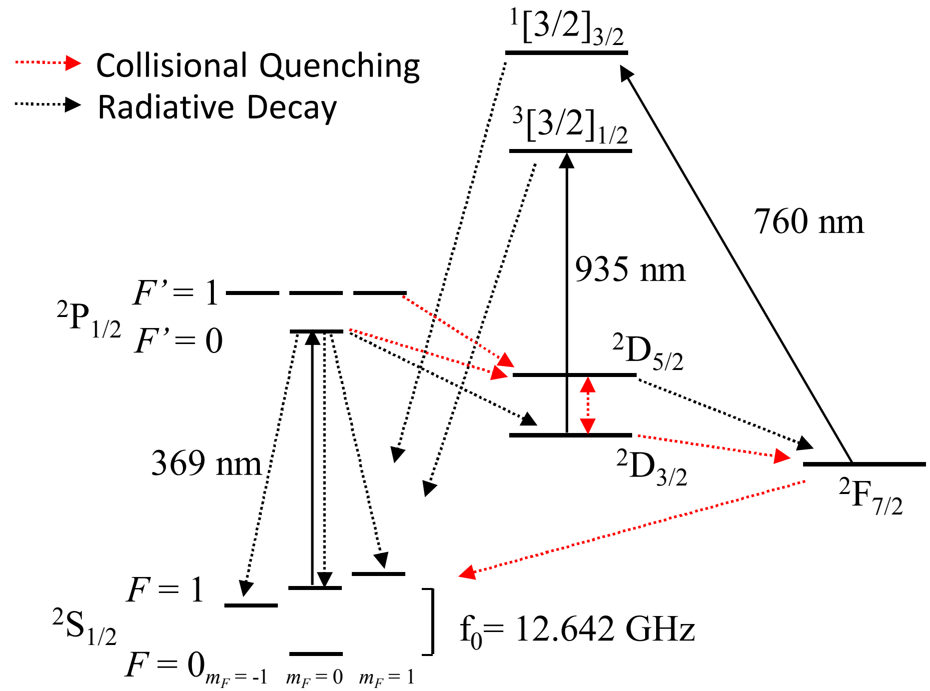


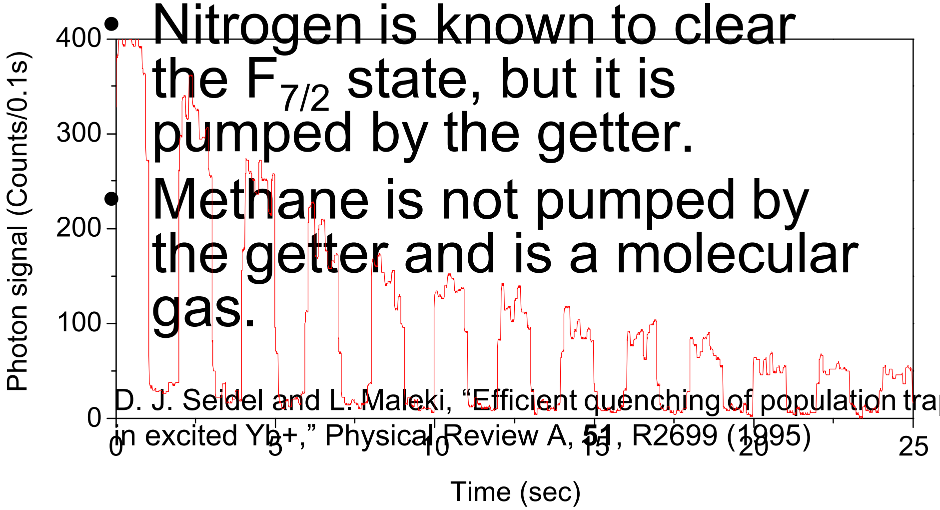




F-State Trapping Problem

- Collisions of Yb ions in the $P_{1/2}$ and $D_{3/2}$ states with He will transfer Yb ions into the $F_{7/2}$ state.
- Noble gasses do not quench the $F_{7/2}$ state.
- Lasers at 760 nm, 638 nm, or 864 nm will clear the F-state.
  - Another laser is too complicated.
- Nitrogen is known to clear the $F_{7/2}$ state, but it is pumped by the getter.
- Methane is not pumped by the getter and is a molecular gas.





F-State trapping in the 3 cm^3 vacuum package.

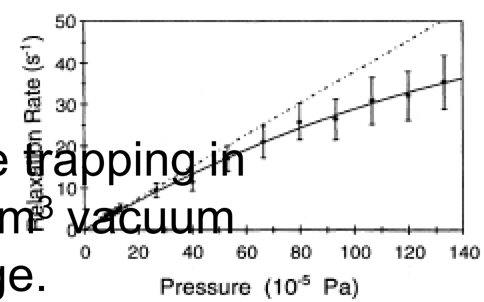
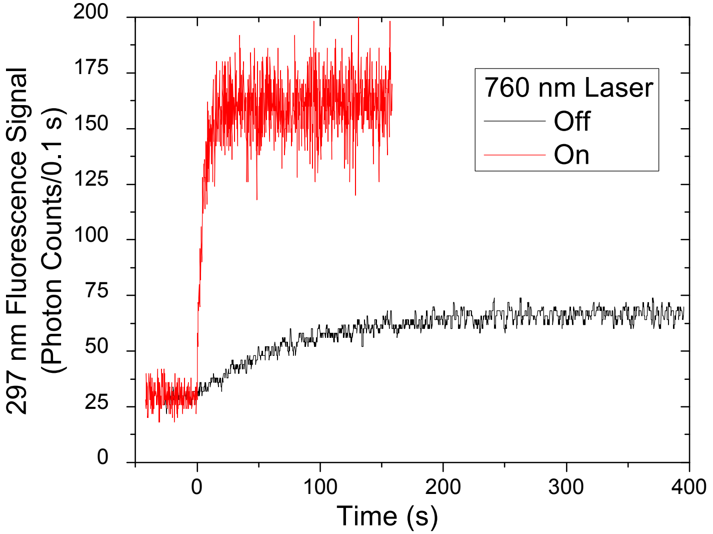


FIG. 3. Quenching rate of ytterbium's trap state vs N_2 buffer-gas pressure. The curved line represents a least-squares fit of the data to the polynomial $\Gamma_{31} = aP + bP^2$; $a = 3.63 \pm 0.12 \times 10^4$/s Pa and $b = -7.45 \pm 1.15 \times 10^6$/s Pa^2, while the straight line represents a linear least-squares fit to pressures $\leq 26.6 \times 10^{-5}$ Pa.

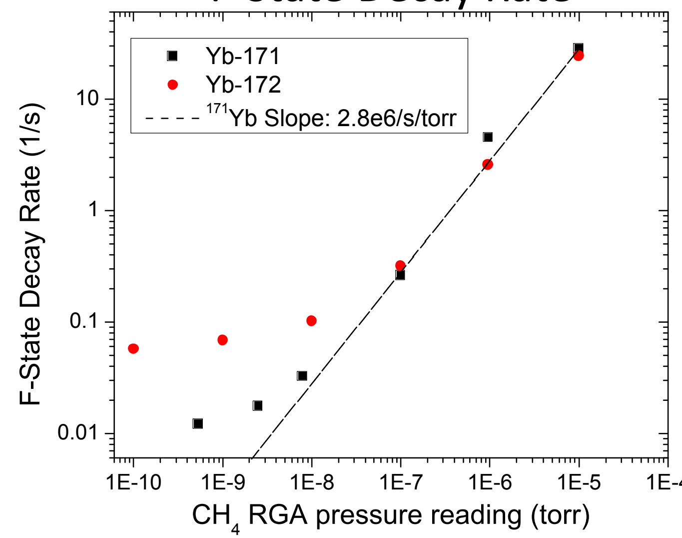
D. J. Seidel and L. Maleki, "Efficient quenching of population trapping in excited Yb+," Physical Review A, 51, R2699 (1995)

Testing Methane as a Quenching Gas

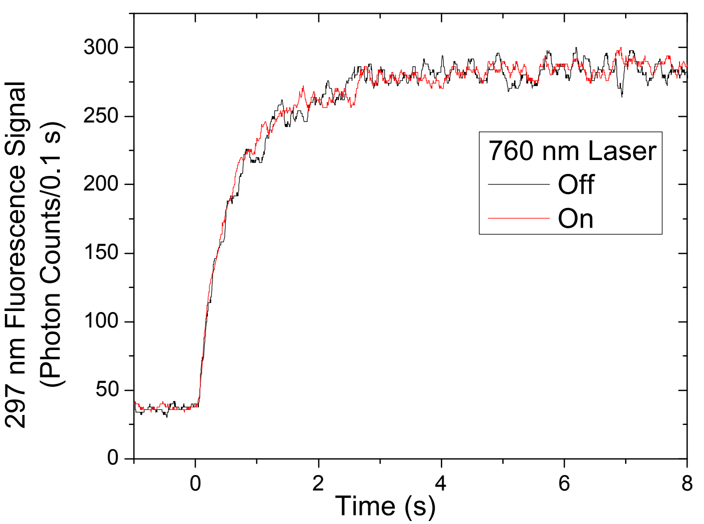
Methane Pressure = 5.3 × 10^{-10}



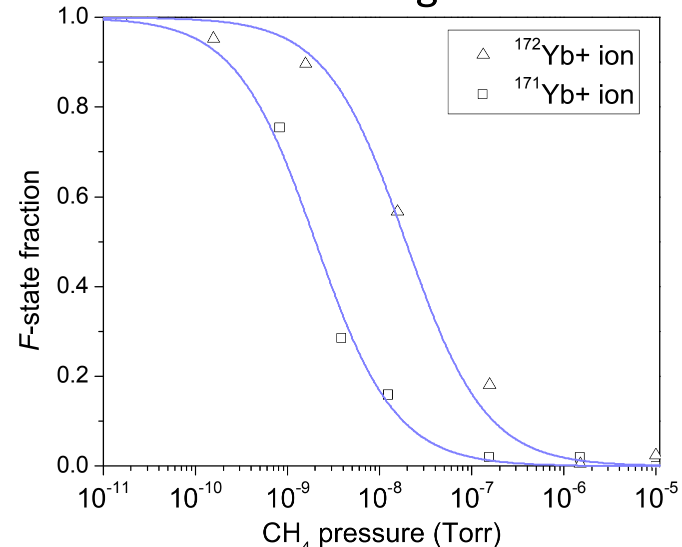
F-State Decay Rate



Methane Pressure = 1 × 10^{-6}



Fraction Remaining in the F-State



Methane Effects on the Clock State

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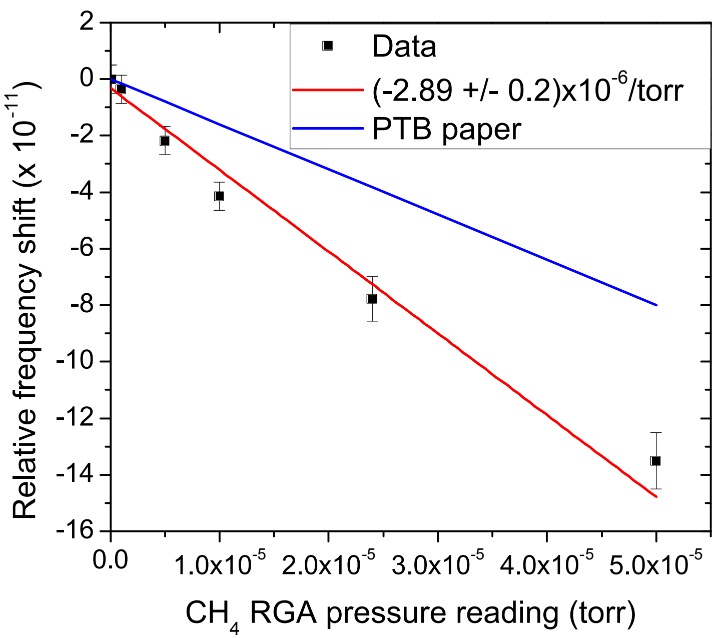
- Estimated methane pressure required for F-State quenching in ^{171}Yb
  - 10^{-8} to 10^{-7} Torr
- F-state Fraction
  - < 20%

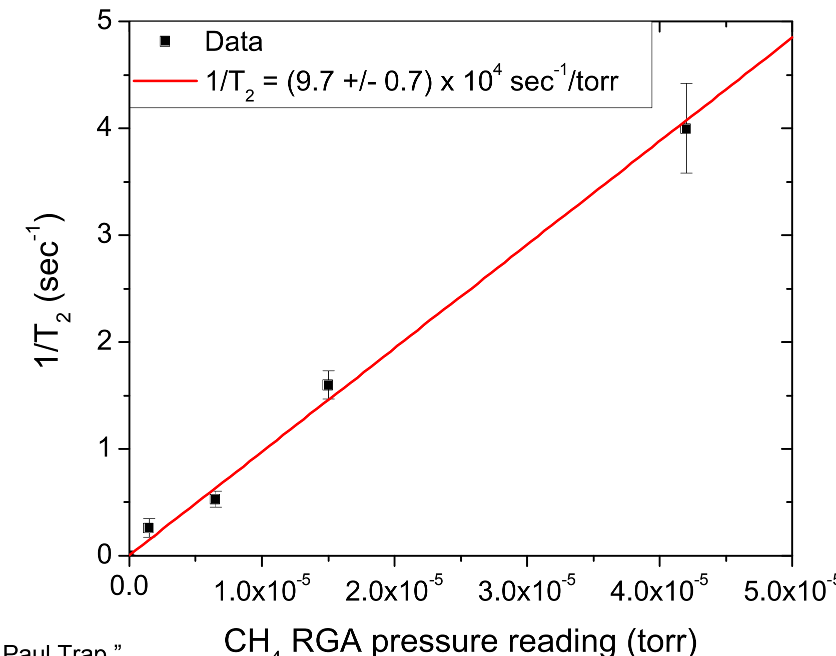
- Effects on the ^{171}Yb ground state
  - Frequency shift due to collisions
    - 10^{-14} to 10^{-13}
  - Relaxation and decoherence of ^{171}Yb ground state due to collisions
    - T_2 = 1000 to 100 s

Frequency Pulling of Methane



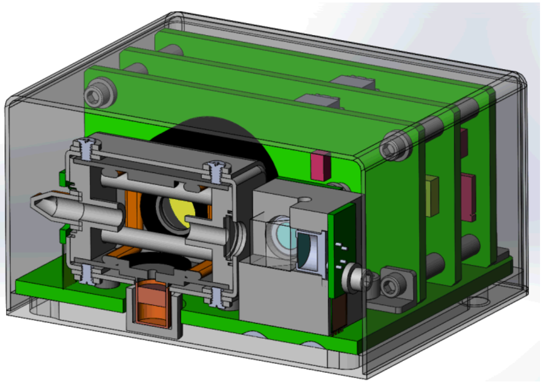
A. Bauch, D. Schnier, and C. Tamm, "Microwave Spectroscopy of 171 Yb+ Stored in a Paul Trap," Proceedings of the 5th Symposium on Frequency Standards and Metrology, pp. 387–388, 1995.

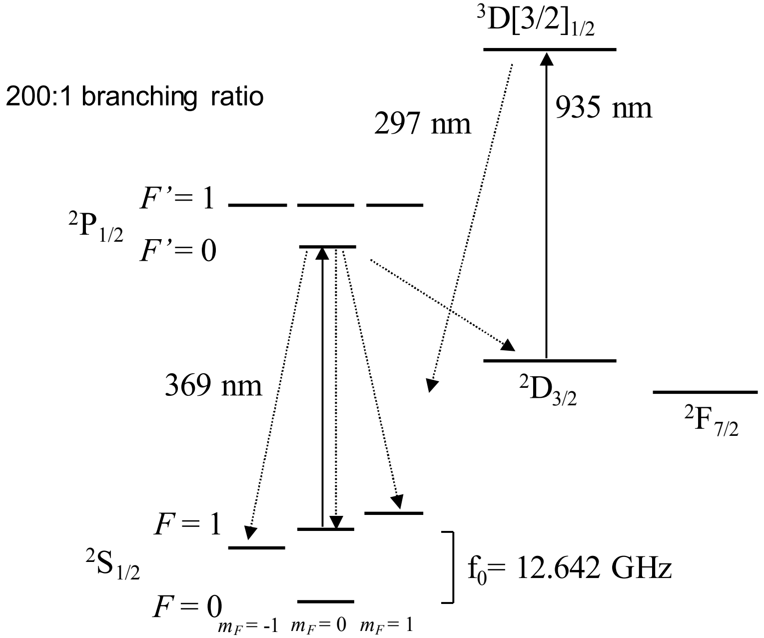
Decoherence Rate in ^{171}Yb Ground State



DARPA ACES
Portable Ion Clock Technology (PICT)

- Optical pumping and detection laser using the first ever VCSEL at 369 nm
  - Power consumption goal: 10 mW
  - Previously the 369 nm laser consumed 300-400 mW
- Microwave Optical Double Resonance (MODR) operation, with ***continuous feedback from the ions***
  - High bandwidth clock and laser locks
  - Previously used pulsed-mode operation
- Design for high SNR by suppressing the scattering of 369 nm light and optimizing collection efficiency
  - Previously used 297 nm fluorescence
- Suppression of the unwanted low lying *F*-state with methane eliminating a laser normally used in Yb^+ frequency standards



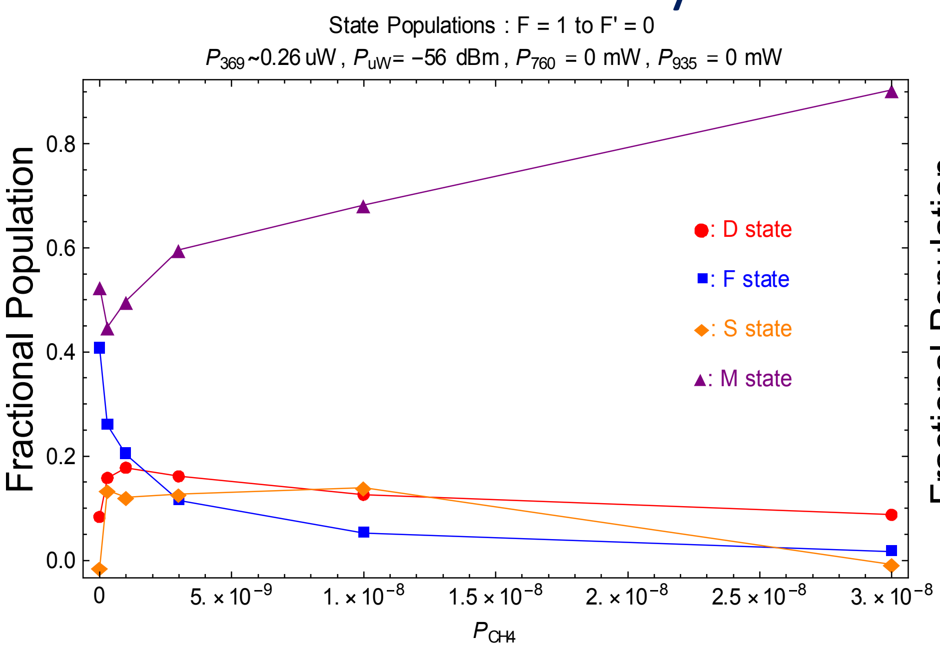


Methane Experiments

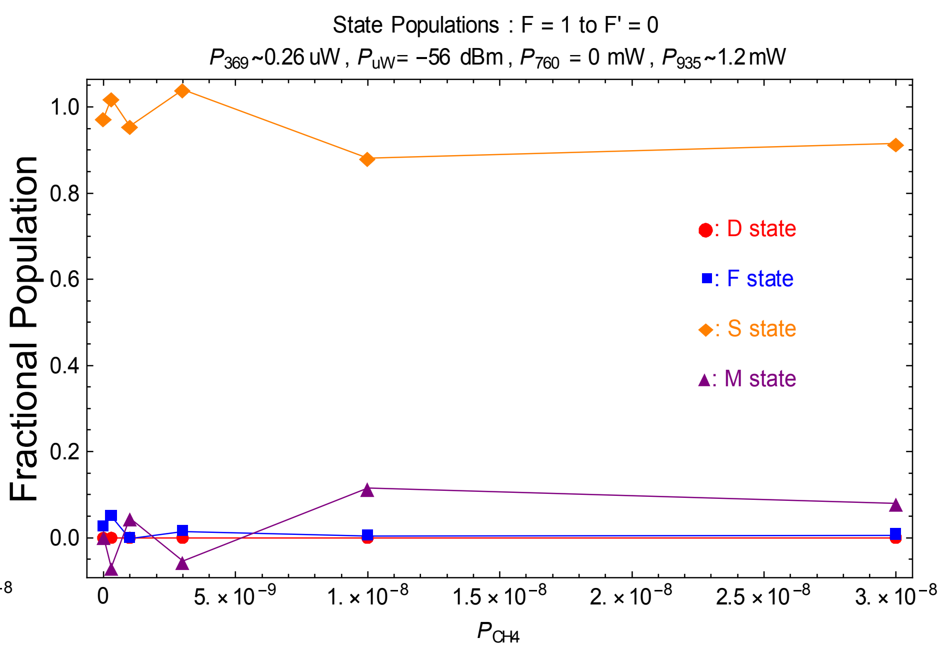
- Set microwave and 369 nm optical power to give 150 Hz linewidth
  - 369 nm laser power: 260 nW
- Observe evidence for formation of YbH^+ molecule

- Increasing methane pressure gives more YbH^+
- Molecule formed out of the $D_{3/2}$ state
- Tuned to a YbH^+ dissociation transition at 369.482 nm and observe rapid signal recovery

369 nm Laser Only

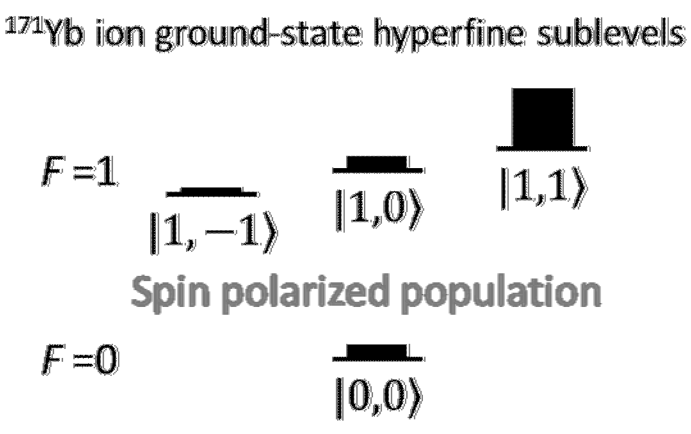


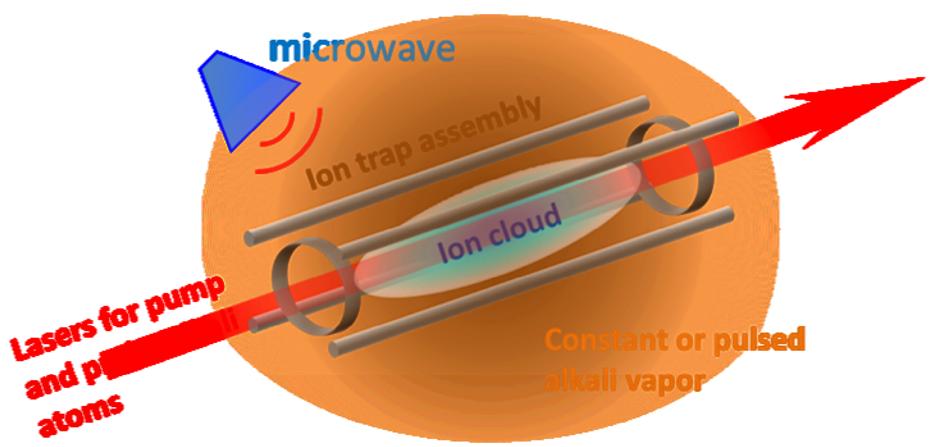
369 nm and 935 nm Lasers



Alkali Mediated Atomic Clock

- **Utilize spin-dependent ion-alkali interactions**
- **Eliminate the UV laser source**
- **Use NIR laser technology for alkali-metal atoms, which is significantly more mature.**
- **No F-state and D-state clear required.**
- **Challenges: Need large ion-alkali spin exchange cross section, small ion-alkali ion charge exchange**

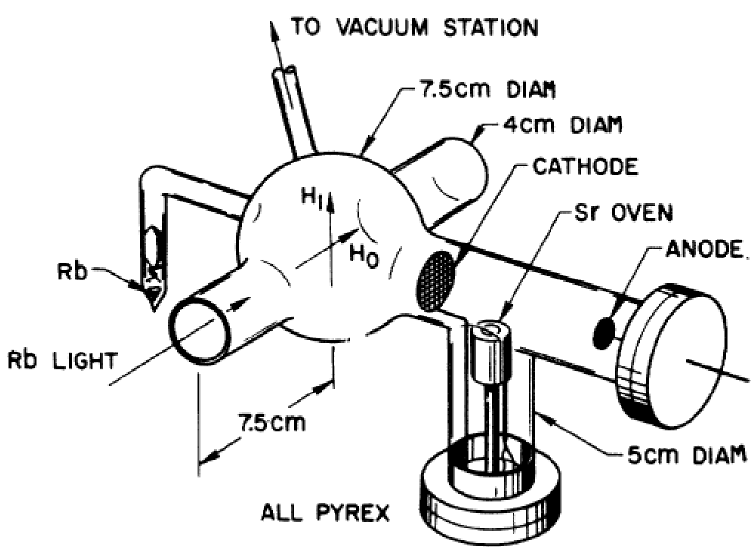


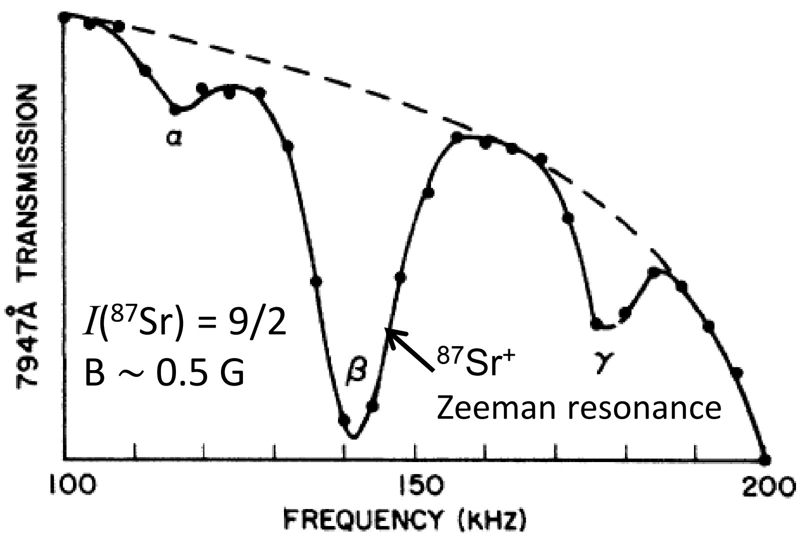


Technical Approach
History of Alkali-Mediated RF Spectroscopy of Ions

- From 1965 to 1969, $^{3}He^{+}$ hyperfine splitting frequency was precisely measured to be (8 665 649 867(10) Hz) via thermal Cs.
- In 1971, Zeeman resonances of Sr^{+} and Cd^{+} were measured via thermal Rb.
- In 1973, Zeeman resonances of Hg^{+} was measured via thermal Rb.
- In 2013, Rb-Yb^{+} spin-exchange interaction was utilized in the ultracold Rb-Yb^{+} system.

Experiment of Sr^{+} Zeeman spectroscopy via Rb-$^{87}Sr^{+}$ spin-exchange:





RF-Stimulated-Raman for continuous microwave interrogation

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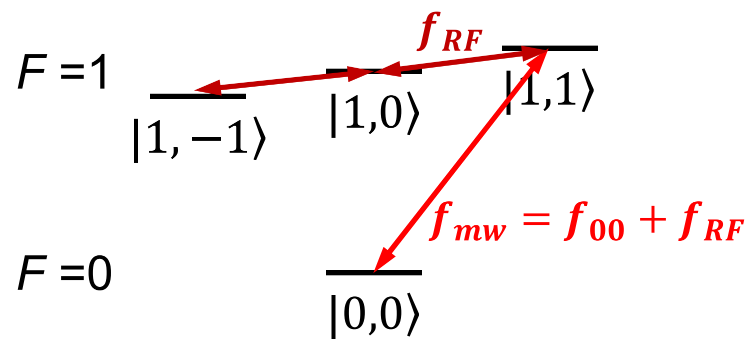
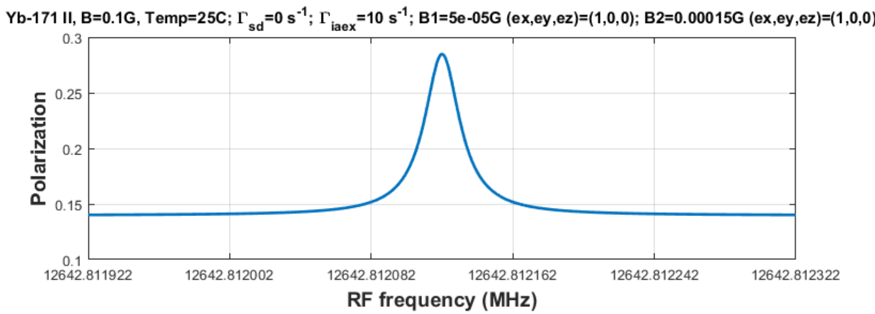
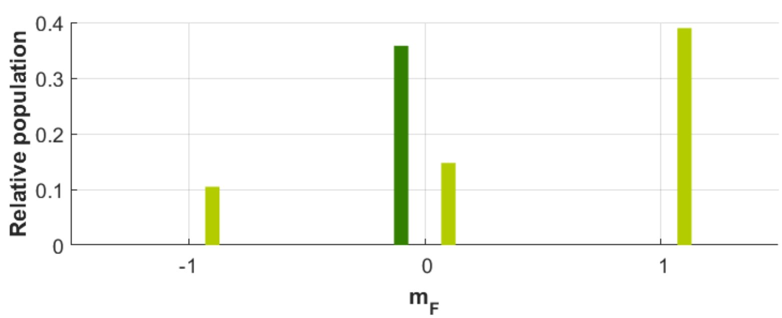
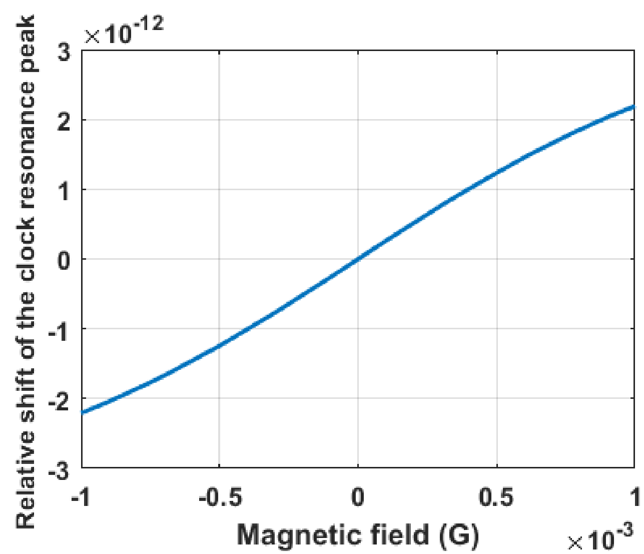
- Full-level density matrix modeling.
- RF-stimulated-Raman interrogation give a good signal.
- When $f_{mw} - f_{RF} = f_{00}$, a spin-polarization peak shows up



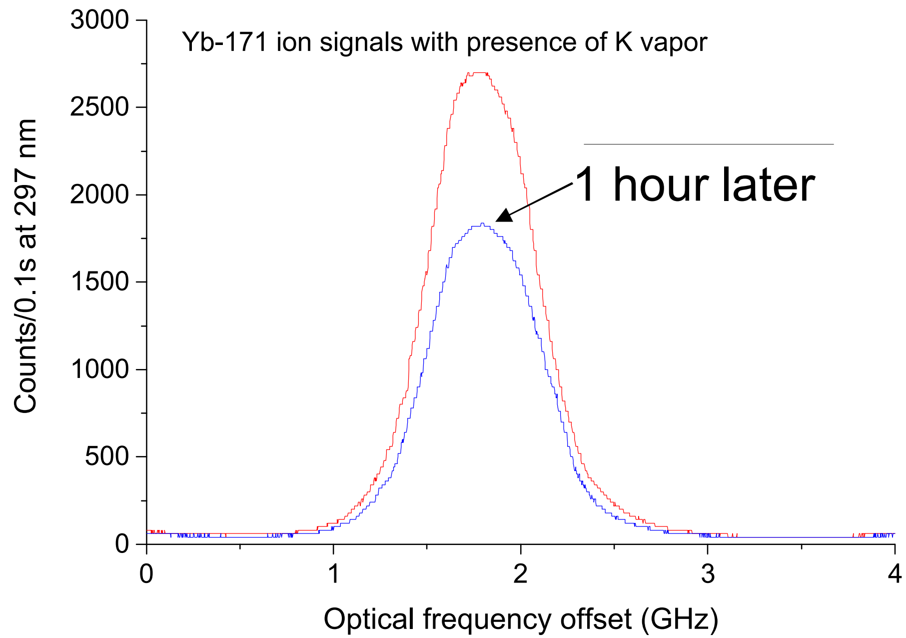






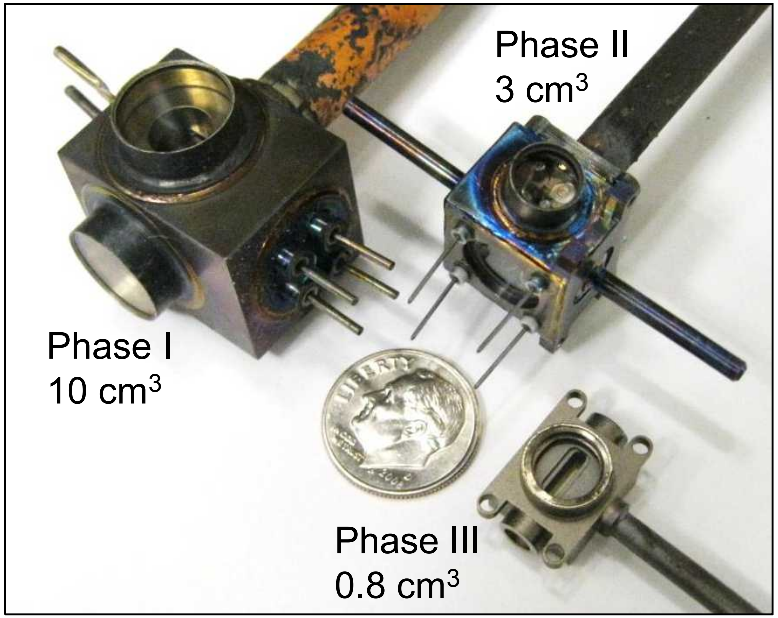
Current Status

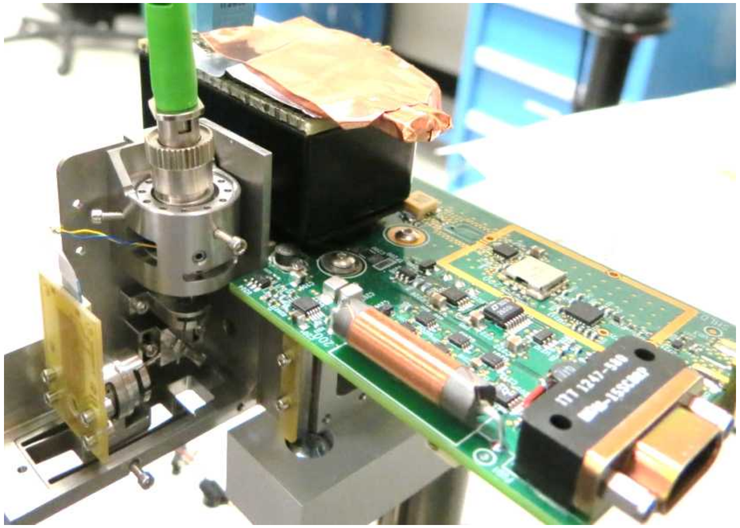
- Trapped ions in the presence of potassium
  - Directly detect ion fluorescence
- Trapped ion lifetime reduce with the potassium getter
  - Likely due to other gasses
  - Evidence for photo association due to the 369 nm light
  - Ion-alkali charge exchange not a limiting factor



Conclusion

- Developed a clock prototype using the sealed 3 cm^3 vacuum package
  - Long-term stability: 6×10^{-14} @ 1 month
- Complete integrated physics package shows $2 \times 10^{-11} /\sqrt{\tau}$
  - Power: < 1 W, Size: < 100 cm^3
- Hybrid metal/ceramic vacuum package shows $2 \times 10^{-11} /\sqrt{\tau}$
- Solved many problems and developed new technologies
  - Miniature vacuum packages
  - Simple ionization technique
  - F-state quenching with methane
  - Miniature Yb sources
  - 740 nm VCSELs
  - Low-power RF drive for the ion trap
- Need for technological improvements
  - 369 nm laser with low-power and long-term stability
  - Low power local oscillator
  - Improve signal-to-noise ratio
    - Detect 369 nm fluorescence





Miniaturized Ion Clock Teams

- IMPACT
  - Peter Schwindt
  - Heather Partner
  - Yuan-Yu Jau
  - Nan Yu
  - John Prestage (JPL)
  - James Kellogg (JPL)
  - Darwin Serkland (JPL)
  - Robert Boye
  - Ron Manginell
  - Matthew Moorman
  - Adrian Casias
  - Dan Boschen (Microsemi)
  - David Mailoux (Microsemi)
  - David Scherer (Microsemi)
  - Igor Kosvin (Microsemi)
- ACES: PICT
  - Richard Overstreet (Microsemi)
  - Peter Schwindt
  - Yuan-Yu Jau
  - Thai Hoang
  - Jeff Hunker
  - Matthew Moorman
- ACES: AMIC
  - Yuan-Yu Jau
  - Peter Schwindt
  - Thai Hoang
  - Jeff Hunker

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Back up slides

3 cm^3 Vacuum Package and Ion Trap

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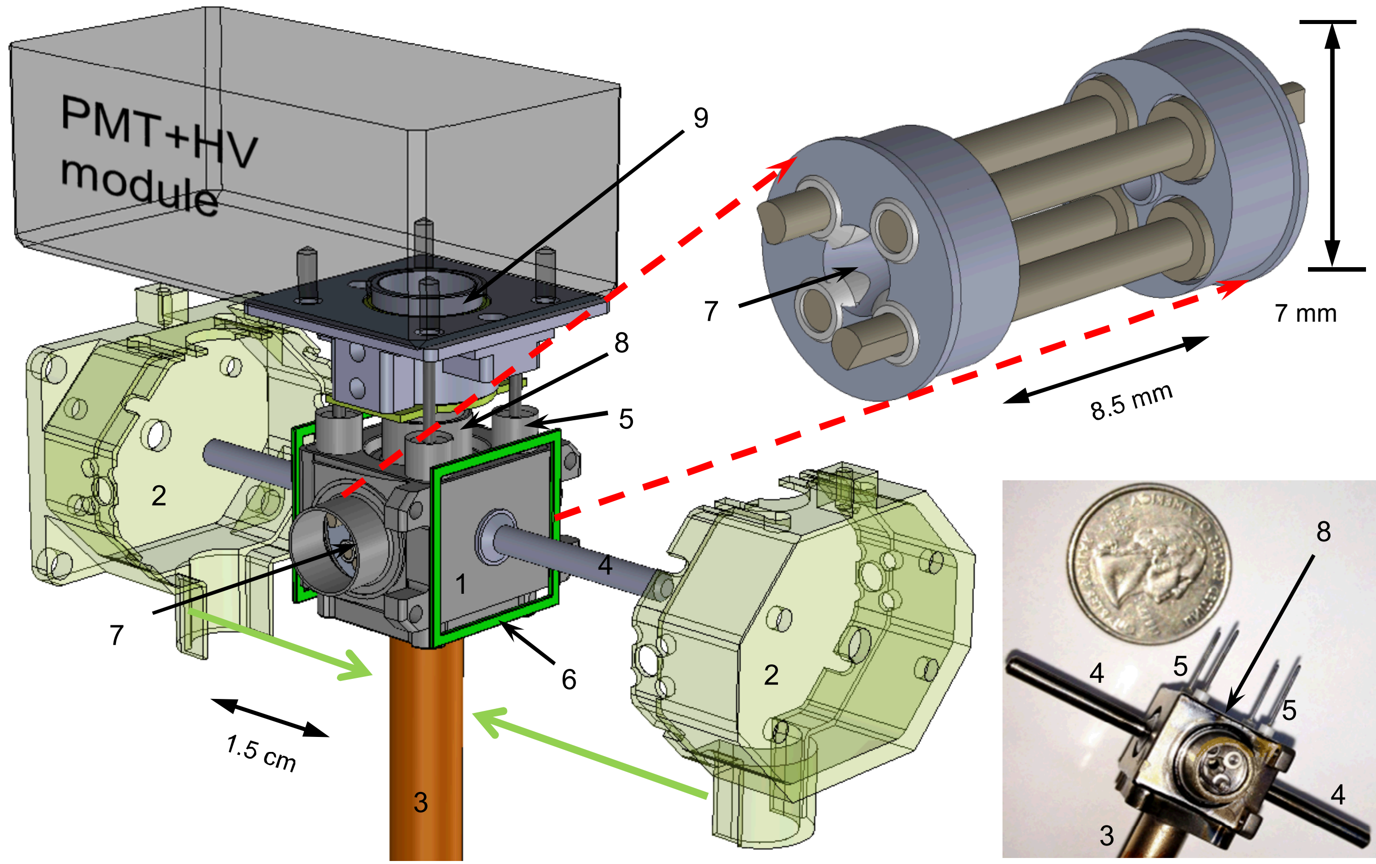
Vacuum package w/ Detector **Ion-trap electrodes**



1. Vacuum package
2. μ-metal shield
3. Copper pump-out tube
4. Yb oven appendage
5. Electrical feedthroughs
6. C-field coils
7. Laser port (sapphire)
8. Fluorescence collection window (sapphire)
9. Lens and filters tube

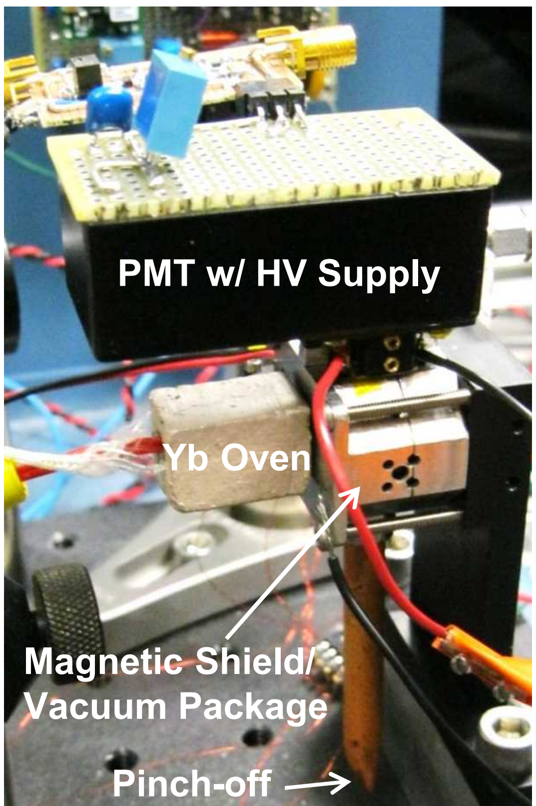
- **Titanium body with sapphire windows.**
- **Linear Quadrupole RF Paul Trap**
- **Pinched off since April 25th, 2012**

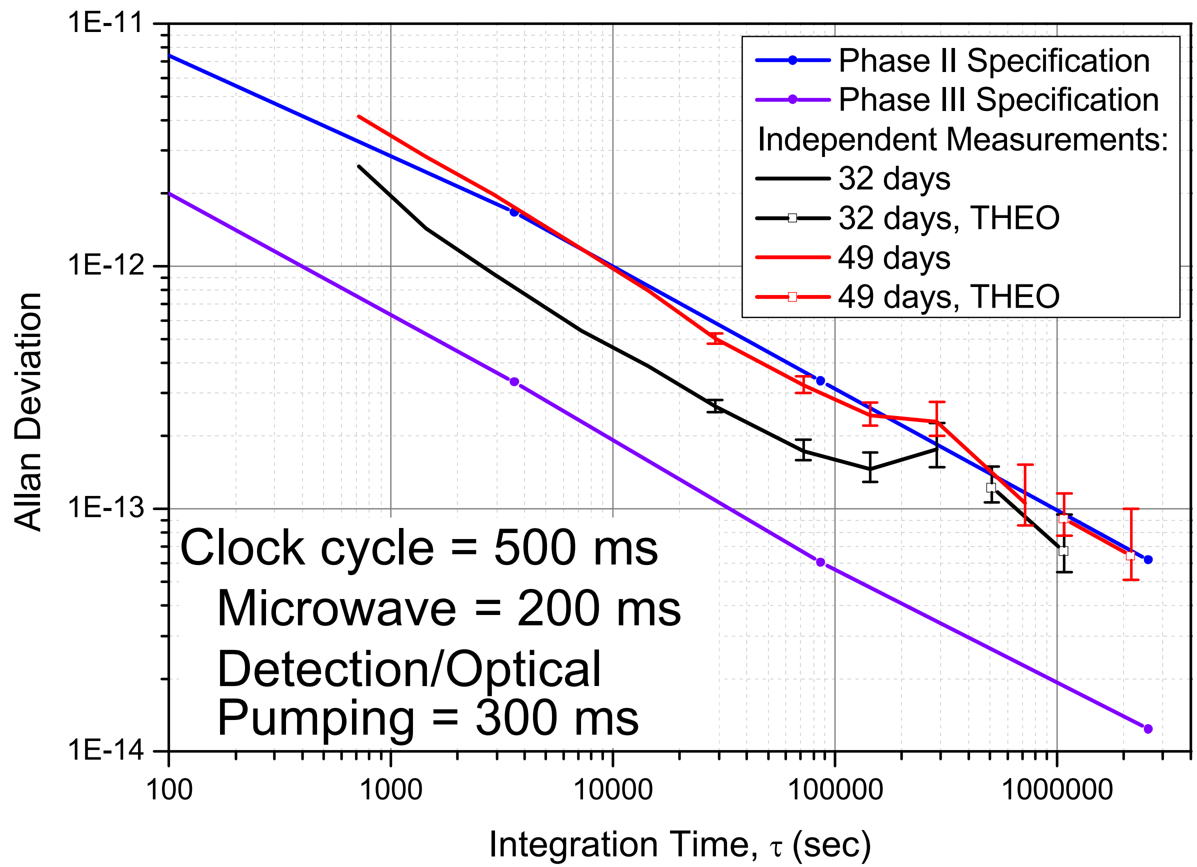
- **Buffer gas cooling with He**
- **Getter Pumped.**
- **Trapped ion lifetime > 3 weeks.**

Independent Testing of Long-Term Stability

- Bread board clock with 935 nm VCSEL and MEMS shutter
- Large doubled 369 nm laser
- Blu-ray burner diode at 405 nm to create ions.
- Allan deviation derived from data sets of 6 days, 26 days, 3 days, 4 days, and 10 days.
- 49 days of data

Integrated Vacuum Package





Miniature Laser Sources

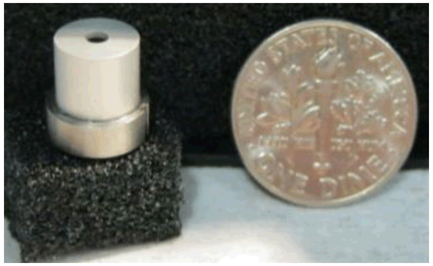
369 nm Direct Diode

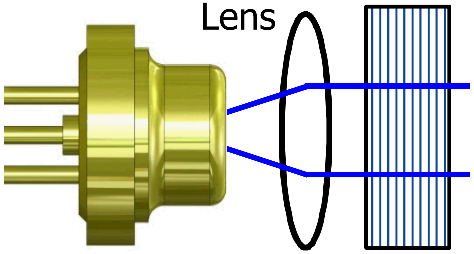
Nichia diode packaged by Ondax. Size: 1 cm^3

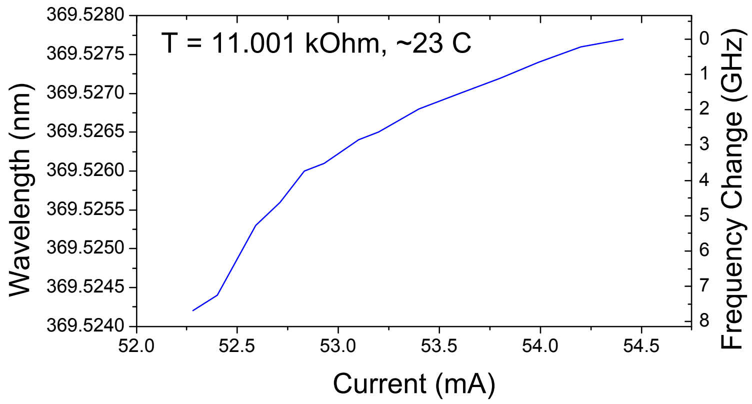
Mode-hop free tuning: 8 GHz

Power consumption: 260 mW (laser) + 100 mW (TEC)

Power output: 1-5 mW







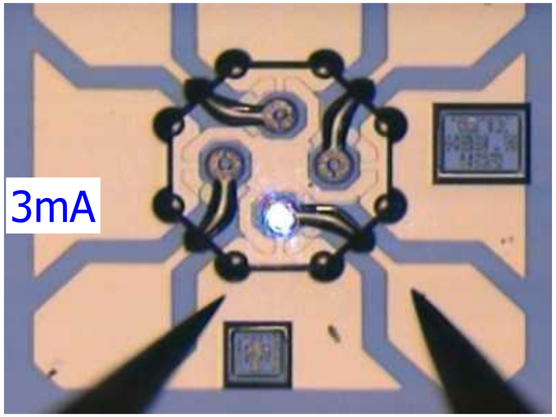
935 nm VCSEL

935 nm VCSEL fabricated at Sandia.

Single mode P > 1 mW

Power consumption: 2.5 mW (laser) + 18 mW (heater)

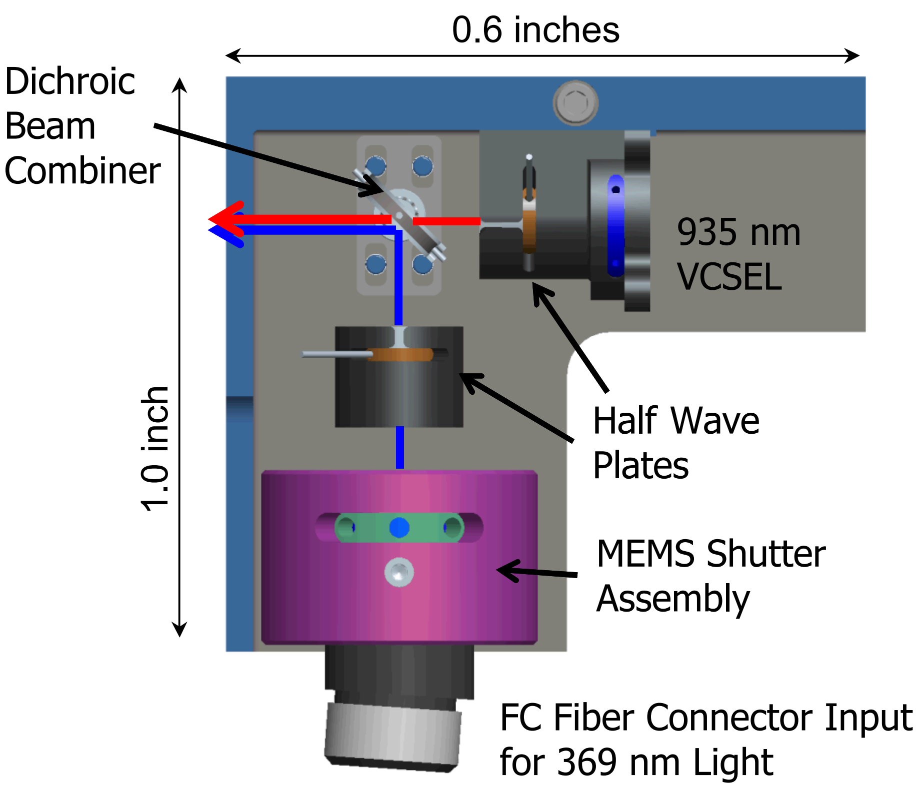
935nm VCSEL (V122571)



Optics Package

Integrated Optics Package

- 369-nm light from an optical fiber: flexibility of sources
- 935-nm VCSEL with temperature control mounted on a PCB
- Mix of adjustable and fixed optical components achieving good overlap of two beam with themselves and with the ions.



369-nm Laser Package

- The package provides temperature control for the 369 nm external cavity diode laser.
- Intensity and polarization control are implemented by the ND filters and the half waveplate (HWP) prior to the light being coupled into the optical fiber.