SAND2015-2724C

Miniature trapped-ion frequency standard with $^{171}Yb^{+}$

Micro Position, Navigation, and Timing Program
Integrated Micro Primary Atomic Clock Technology (IMPACT)
DARPA/MTO

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April 16th, 2015

Sandia National Laboratories

NASA JPL Jet Propulsion Laboratory California Institute of Technology

Microsemi

Microfabricated Ion Frequency Standard Team

Sandia National Laboratories

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- Optics Integration
  - Robert Boye
- Yb Source
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- Miniature Vacuum Package
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- Electronics (Microsemi)
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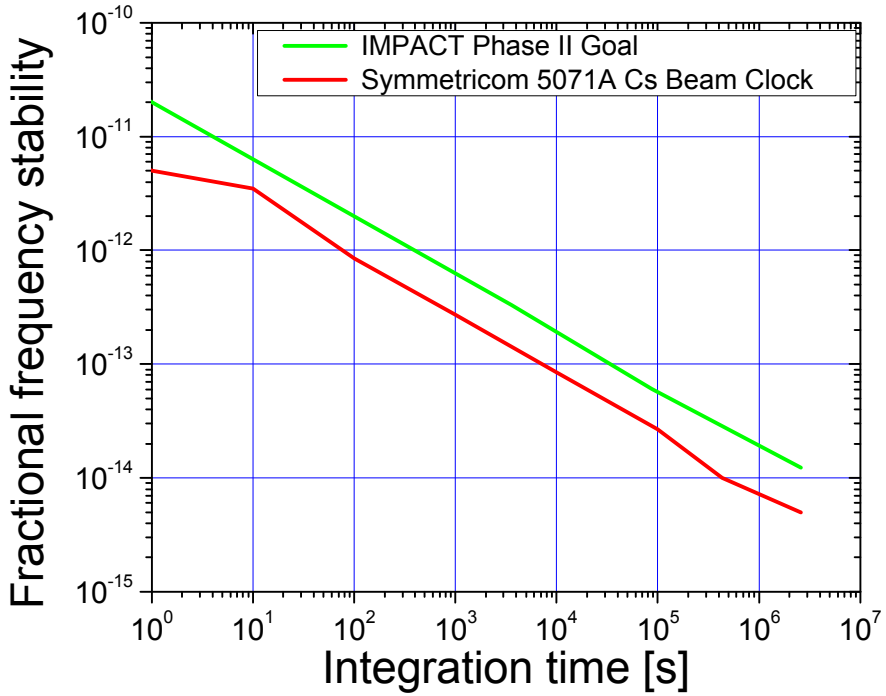
This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions, and/or findings contained in this article/presentation are those of the author(s)/presenter(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

IMPACT Project Goals

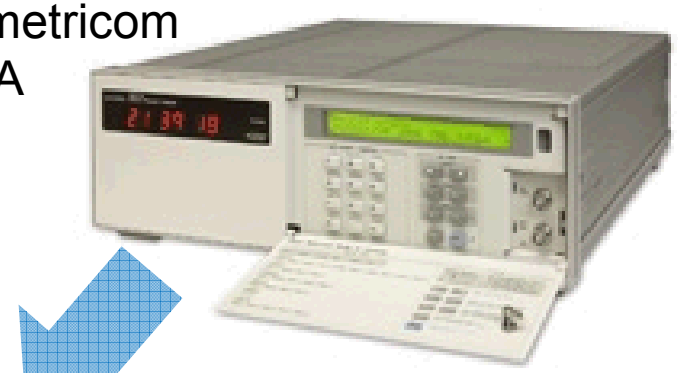
- Achieve Cs Beam Clock performance in a mass and power constrained package
- 5 cm^3, 50 mW, 10^{-14} performance

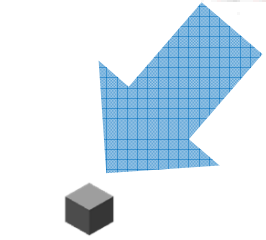


Applications--Excellent timing for:

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

Symmetricom 5071A





Miniature primary frequency standard

Trapped Ion Clock for Miniaturization

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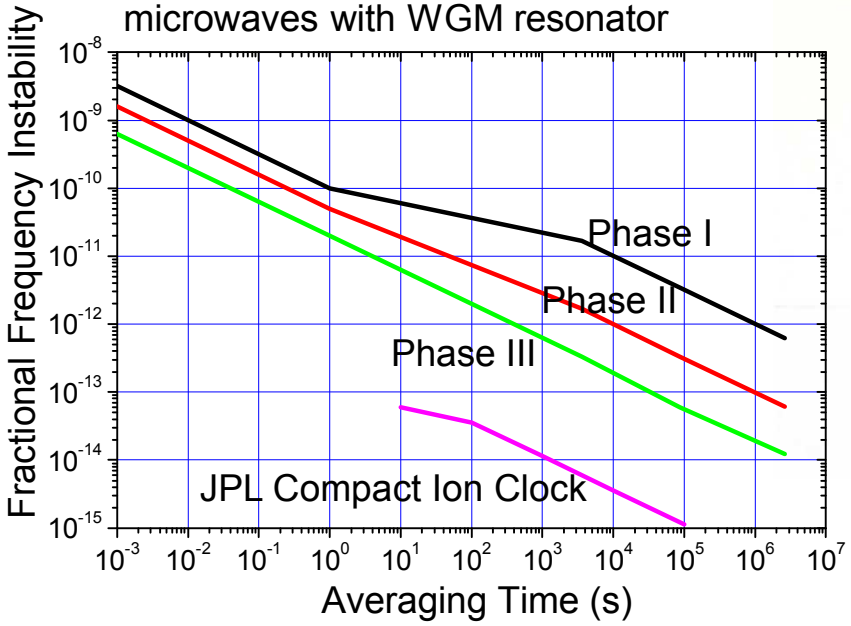
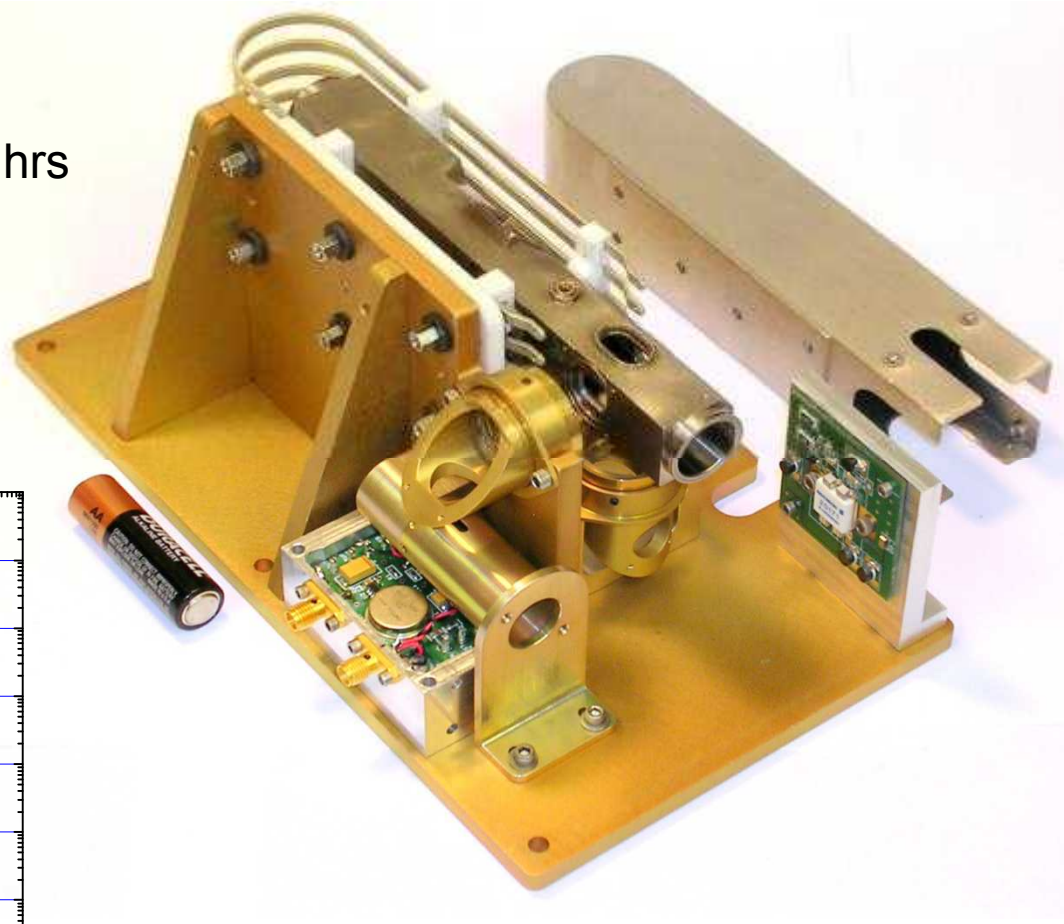
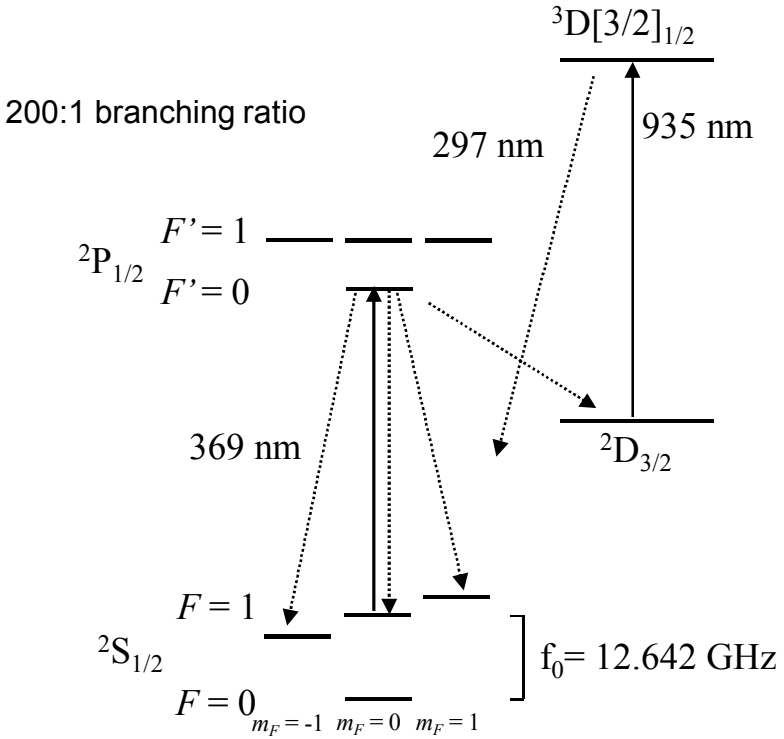
- Trapped ion clocks are already compact while delivering excellent performance.
- Low mass, size, power
- Trapped ion lifetime: up to 10,000 hrs
- Coherence time: > 100s
- Other approaches for IMPACT:
  - Miniature fountain clock
  - Locked optical frequency converted microwaves with WGM resonator

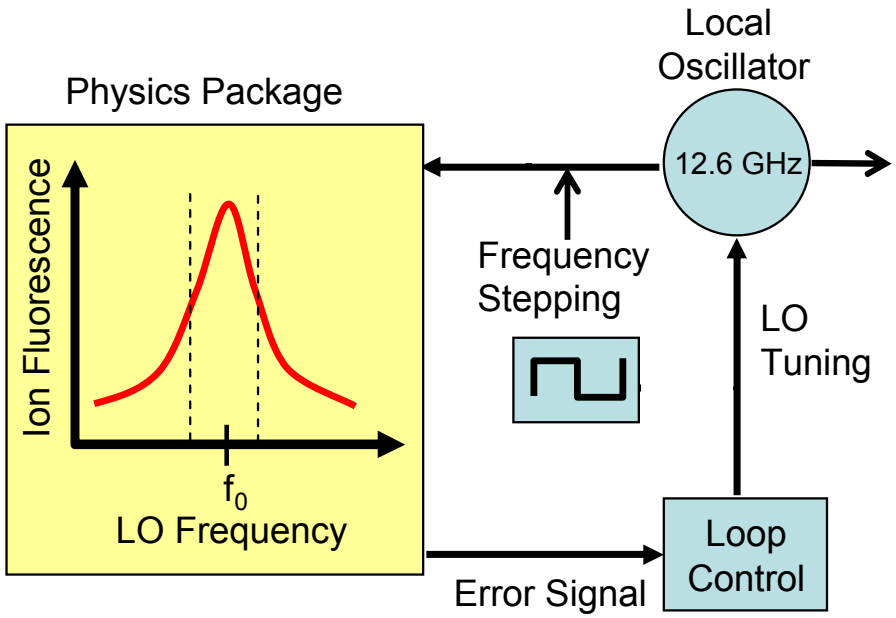


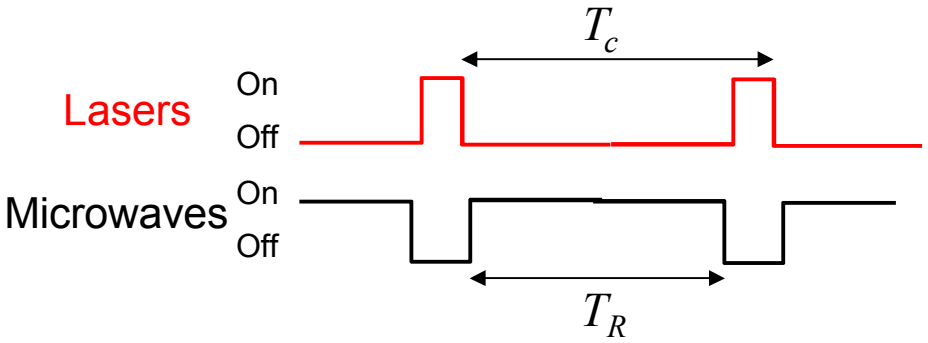


^{199}Hg Trapped Ion Clock from JPL

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







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

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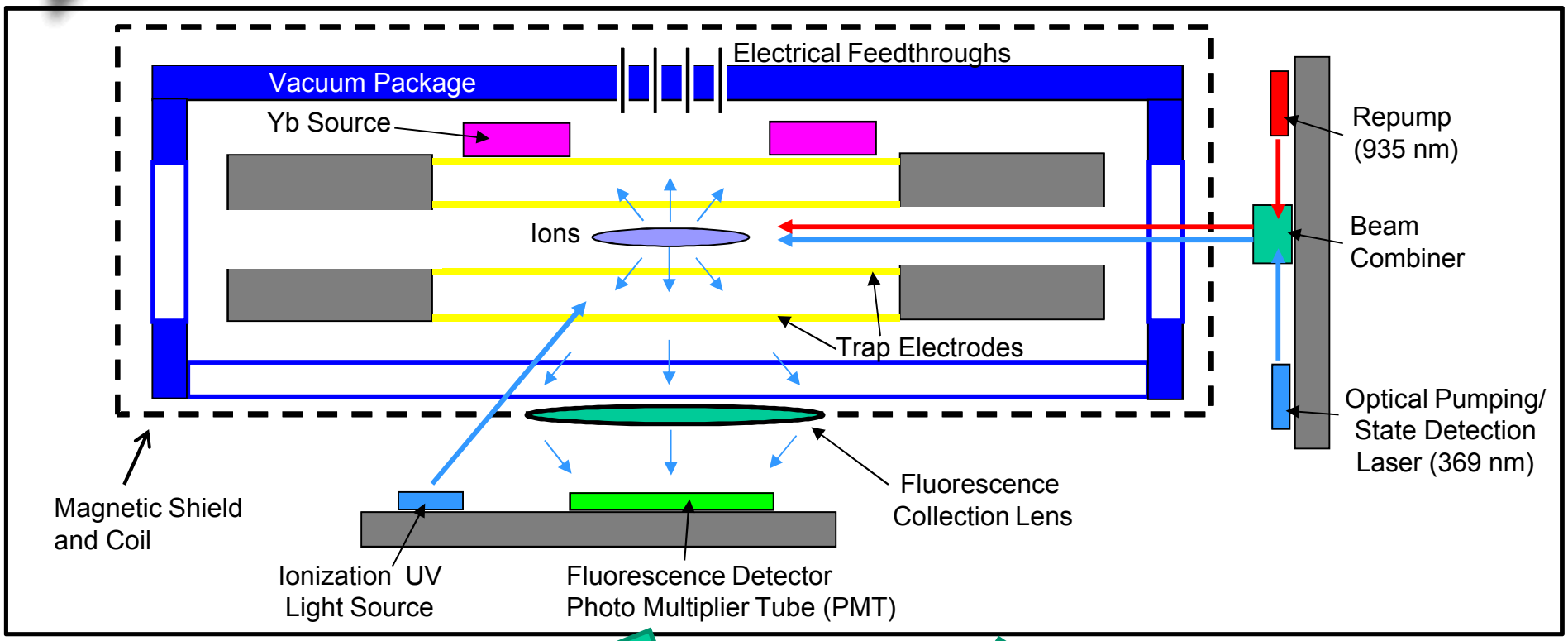

Physic Package

Control and Power Electronics

Local Oscillator

3 cm^3 Vacuum Package and Ion Trap

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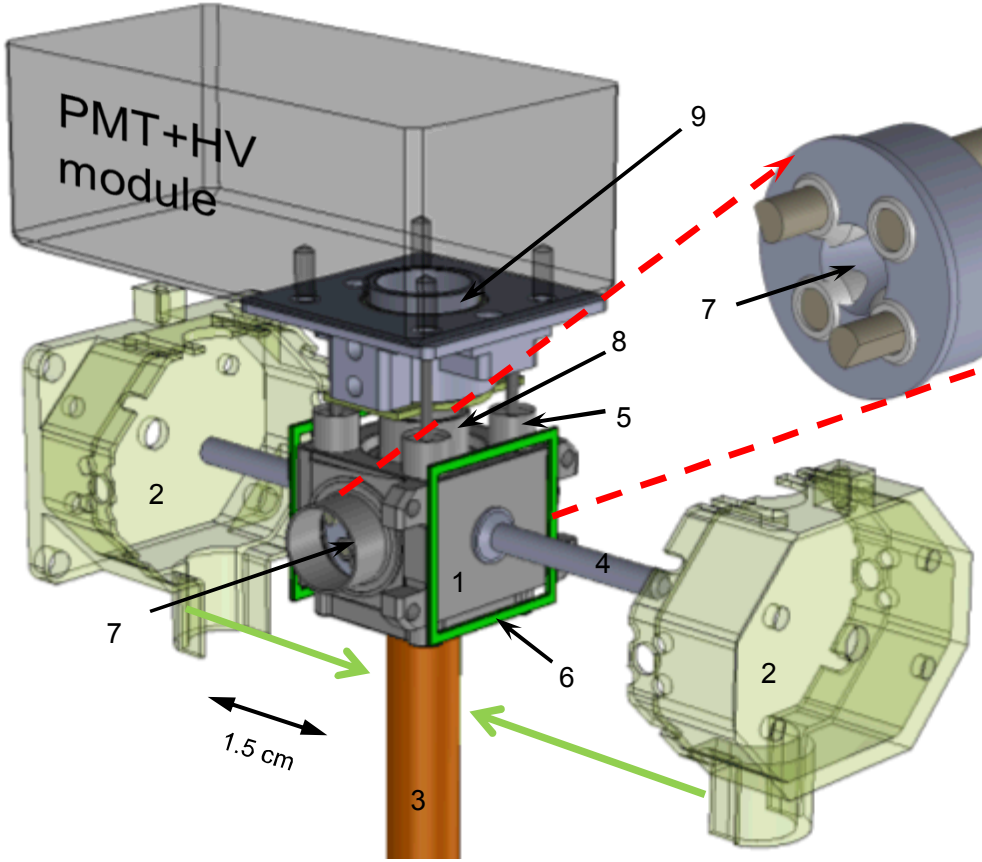
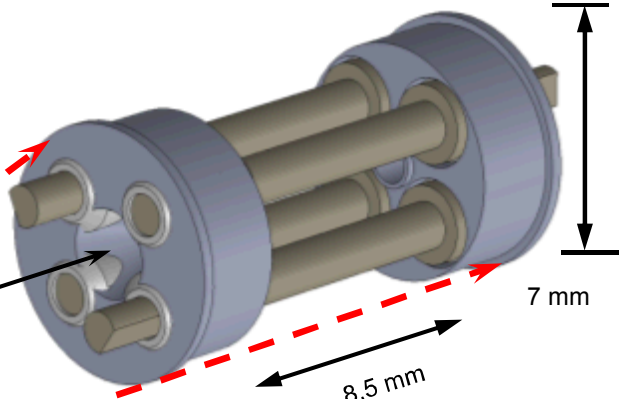
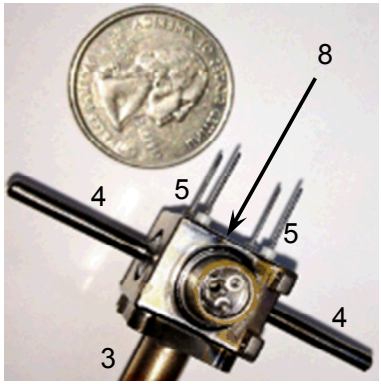
Vacuum package w/ Detector



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

- Getter Pumped.
- Trapped ion lifetime > 3 weeks.

Independent Testing of Long-Term Stability

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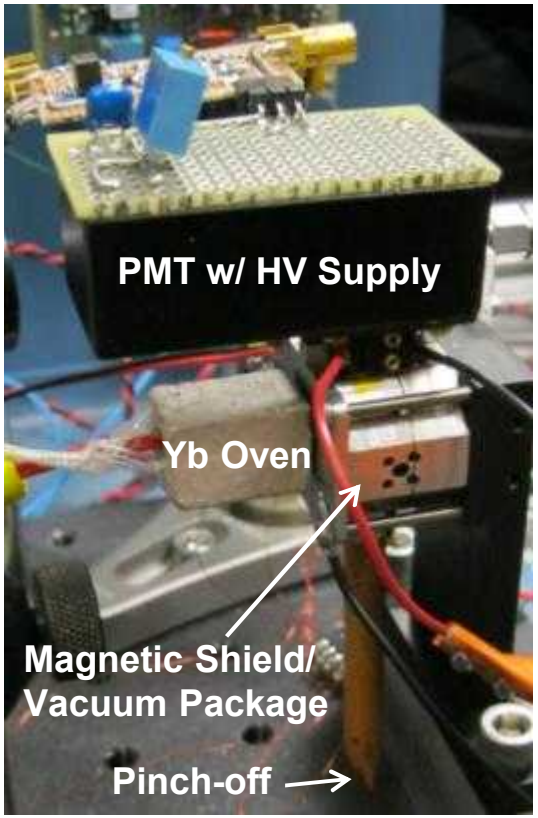
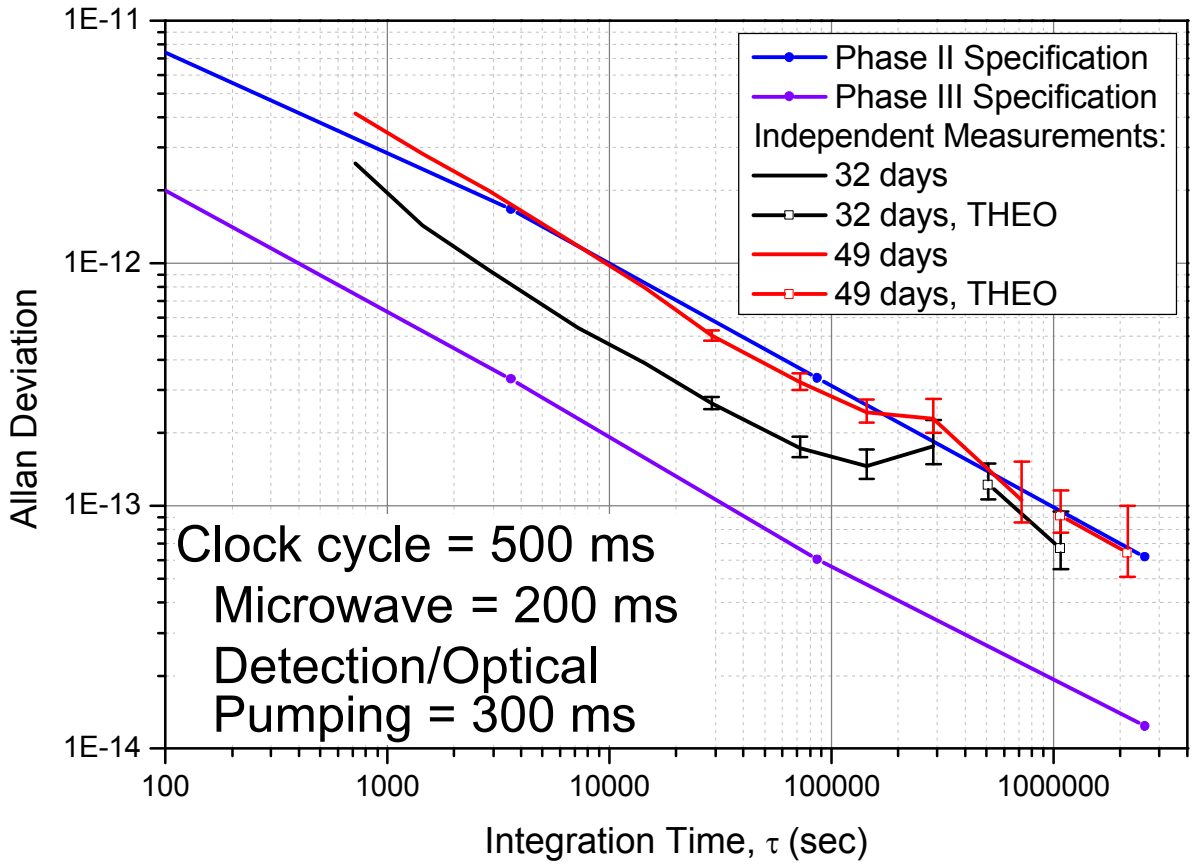
- Bread board clock with 935 nm VCSEL and MEMS shutter
- Large doubled 369 nm laser

- Blu Ray burner diode at 405 nm to creates 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

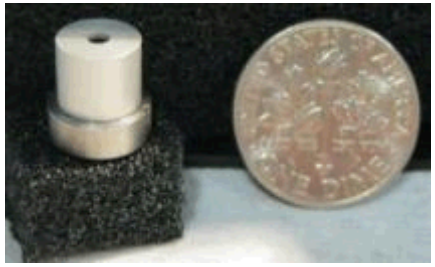
369 nm Direct Diode

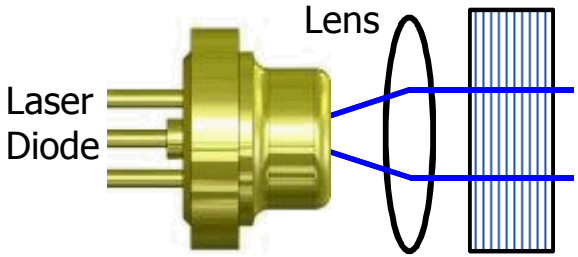
Nichia diode packaged by Ondax. Size: 1 cm^3

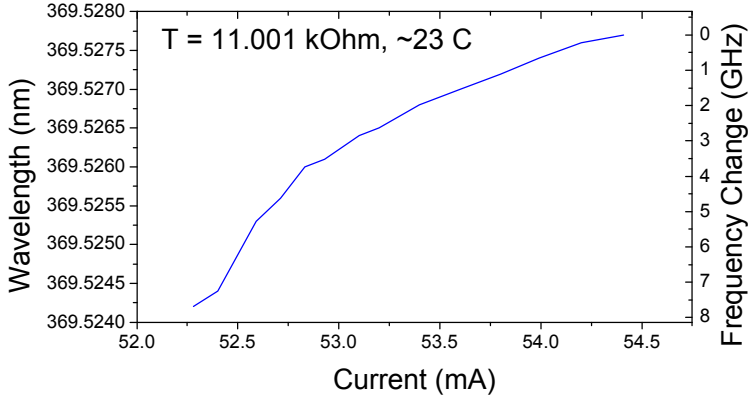
Mode-hop free tuning: 8 GHz

Power consumption: 300 mW

Power output: 1-5 mW







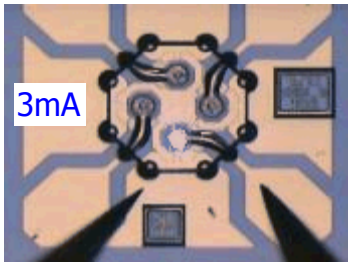
935 nm VCSEL

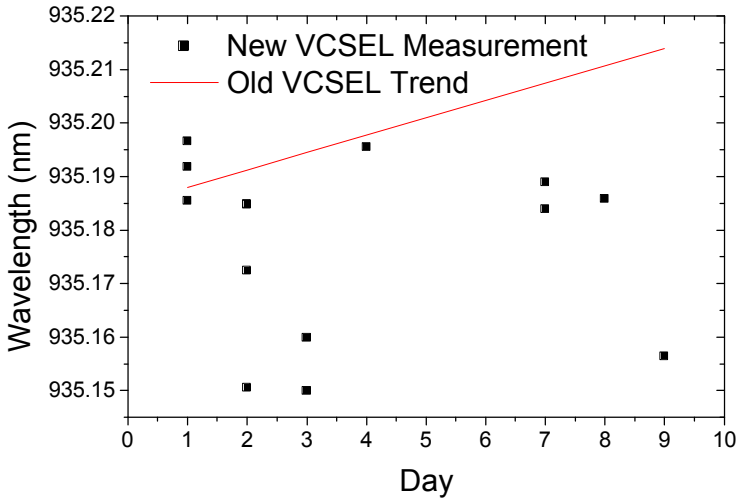
New 935 nm VCSEL fabricated.

Initial results indicate no frequency drift.

Single mode P > 1 mW

935nm VCSEL (V122571)

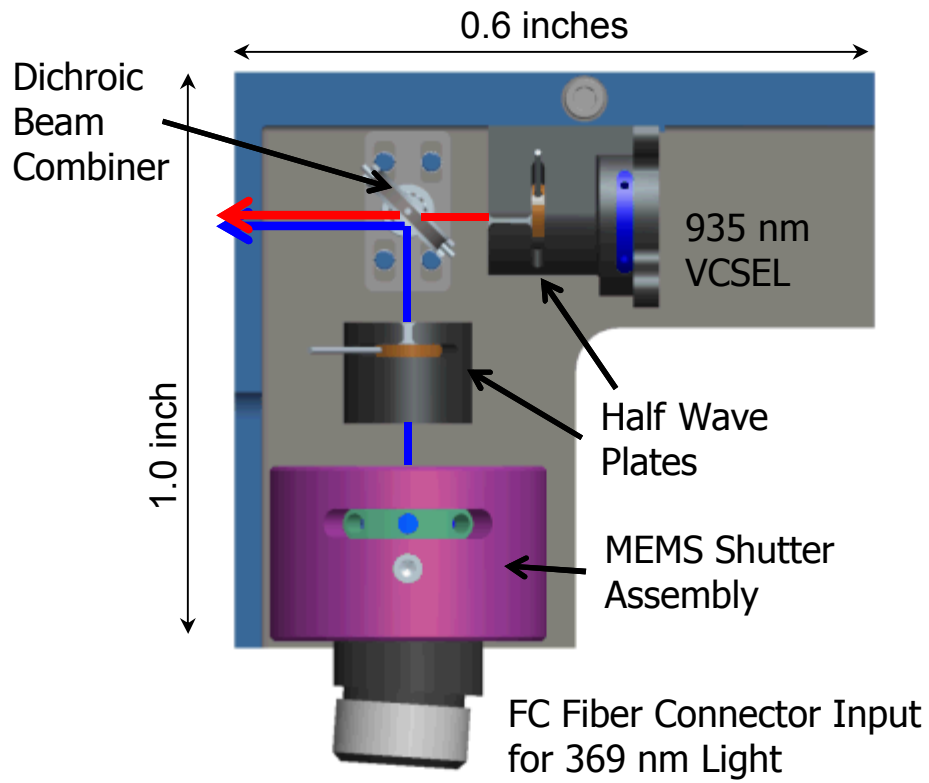




Optics Package

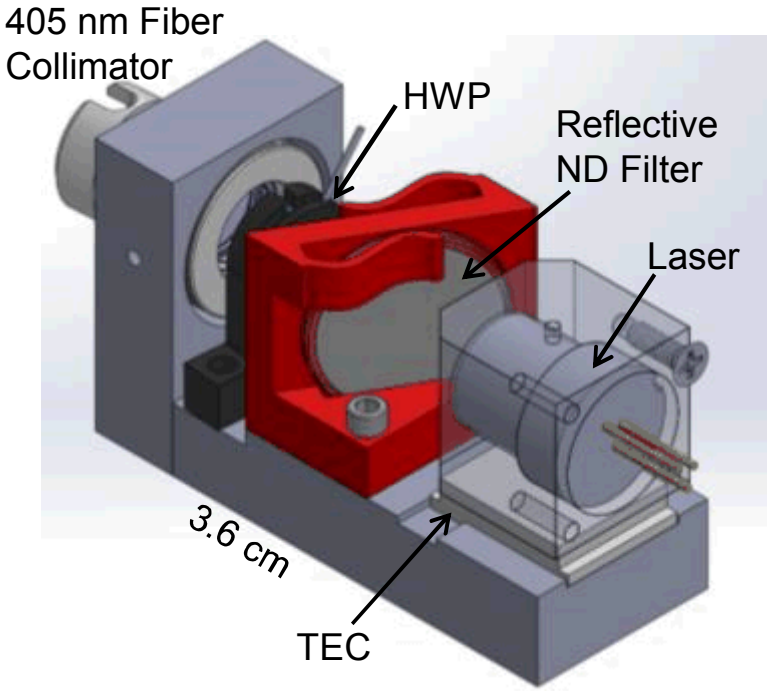
Integrated Optics Package

- 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.

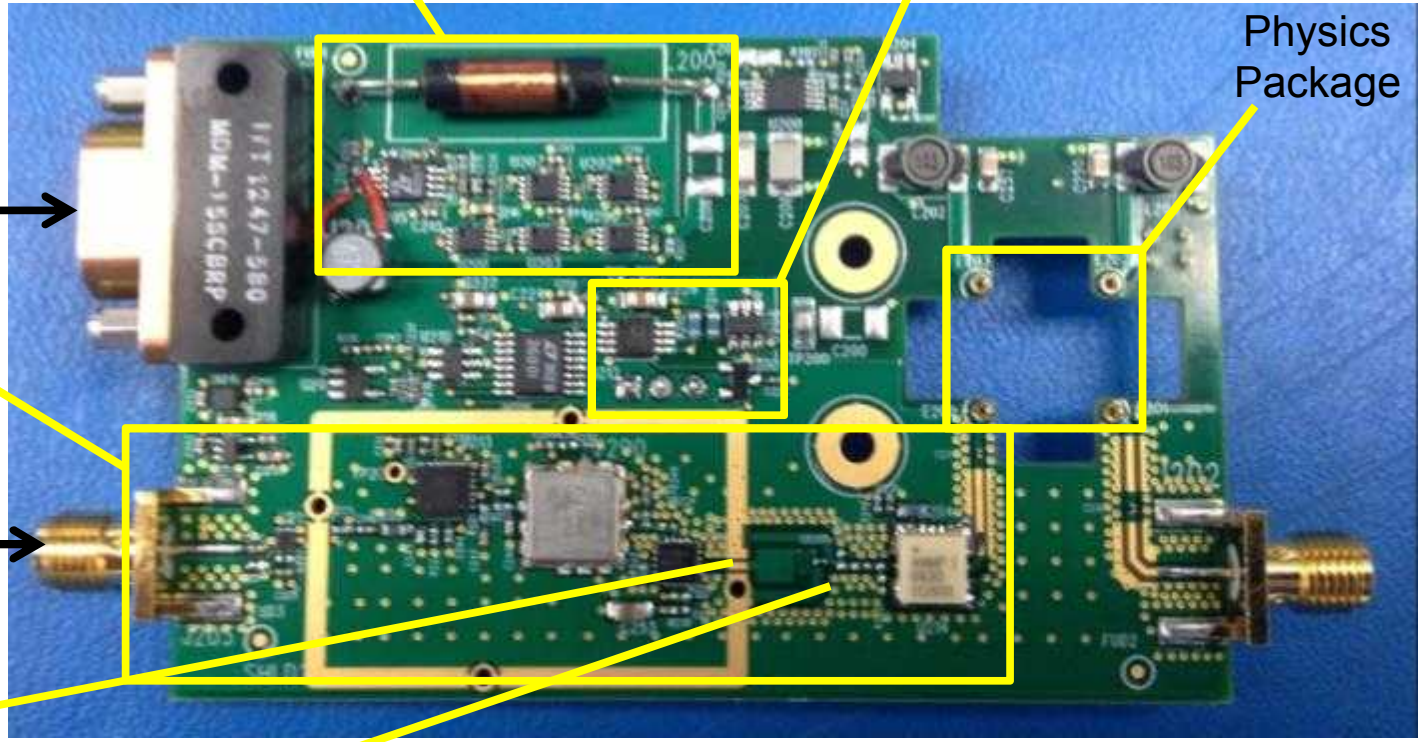


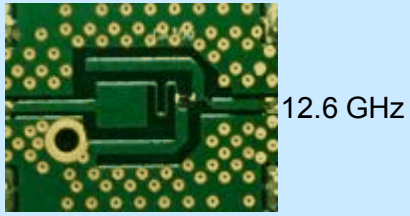
369-nm Laser Package

- 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.



Physic Package Interface Board



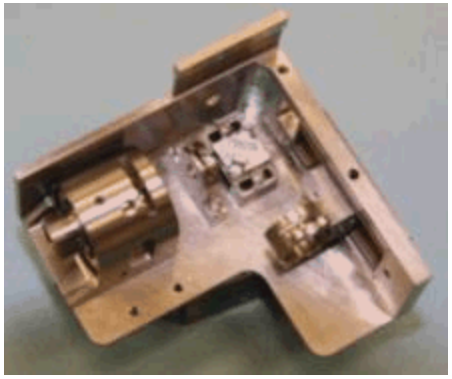


High-efficiency Microwave Doubler

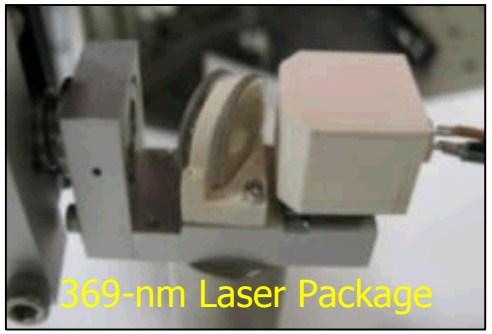
- Digital control of 12.6 GHz frequency and power, and C-field current.
- Study effect of the high voltage RF drive (~200 V_{PP}) on other circuits.

Complete Physics Package

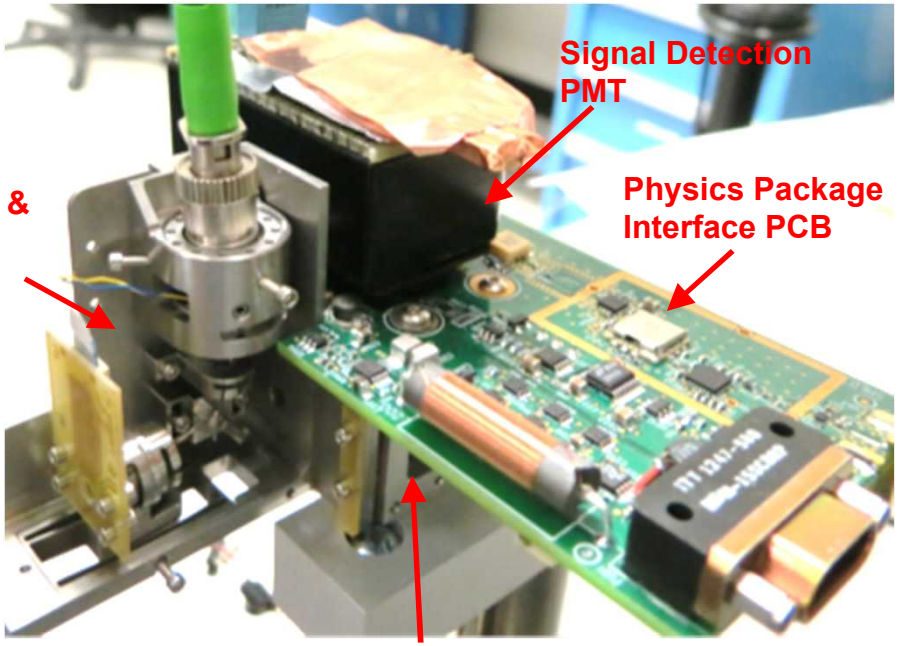
Integrated Optics



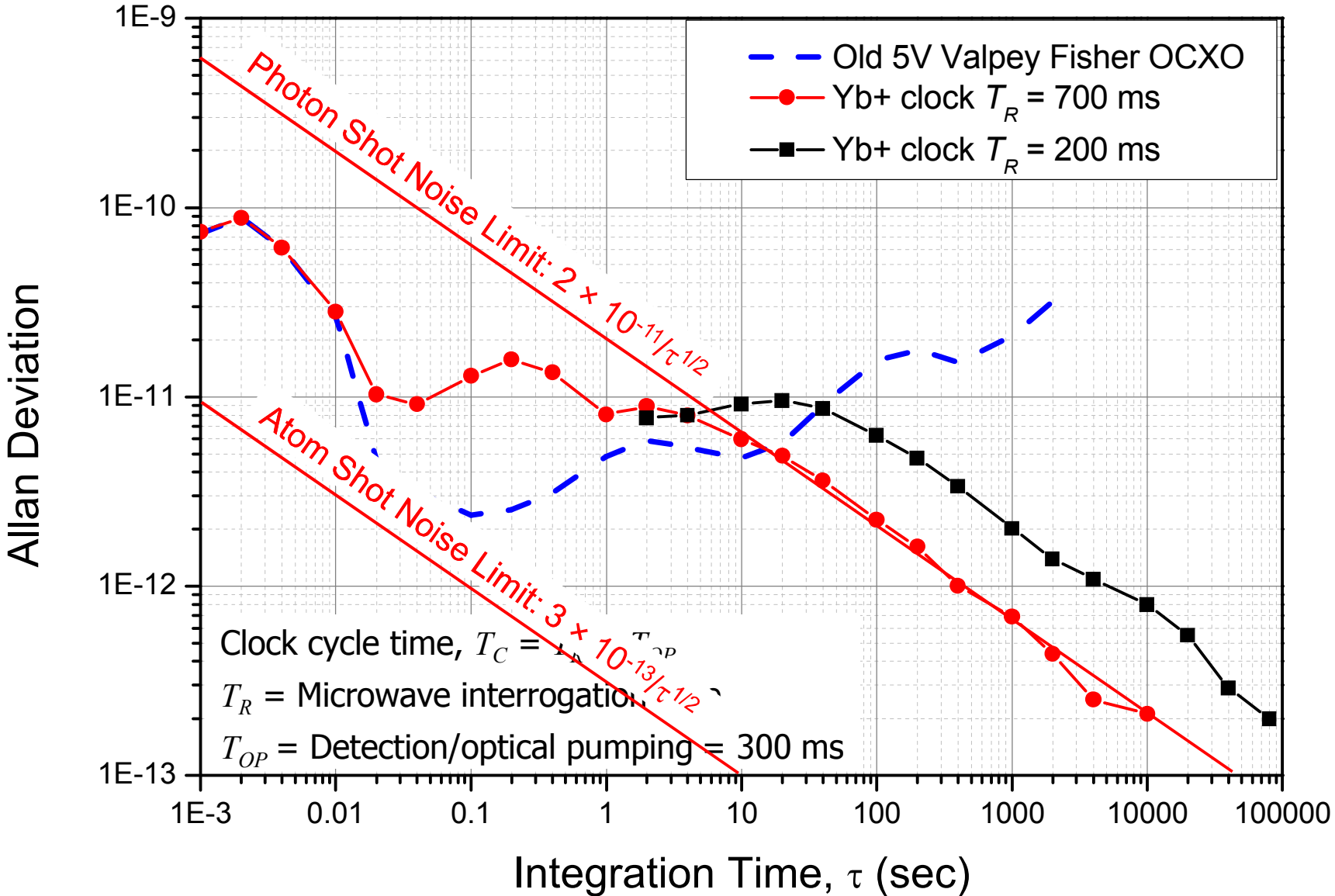
Physics Package Interface



Vacuum Package



Integrated Clock Performance



Co-Fired Hybrid Ceramic/Titanium Package

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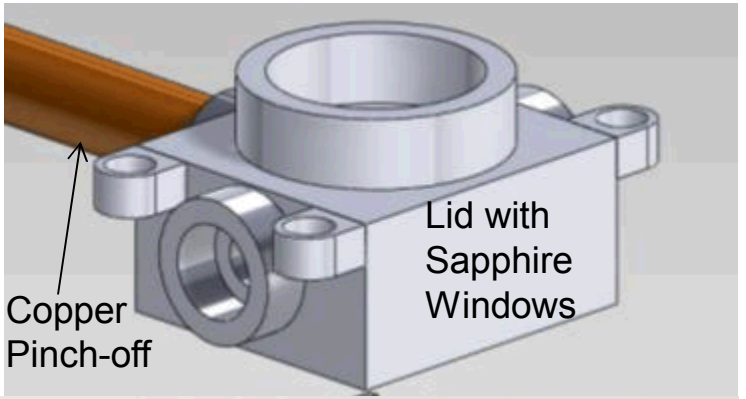
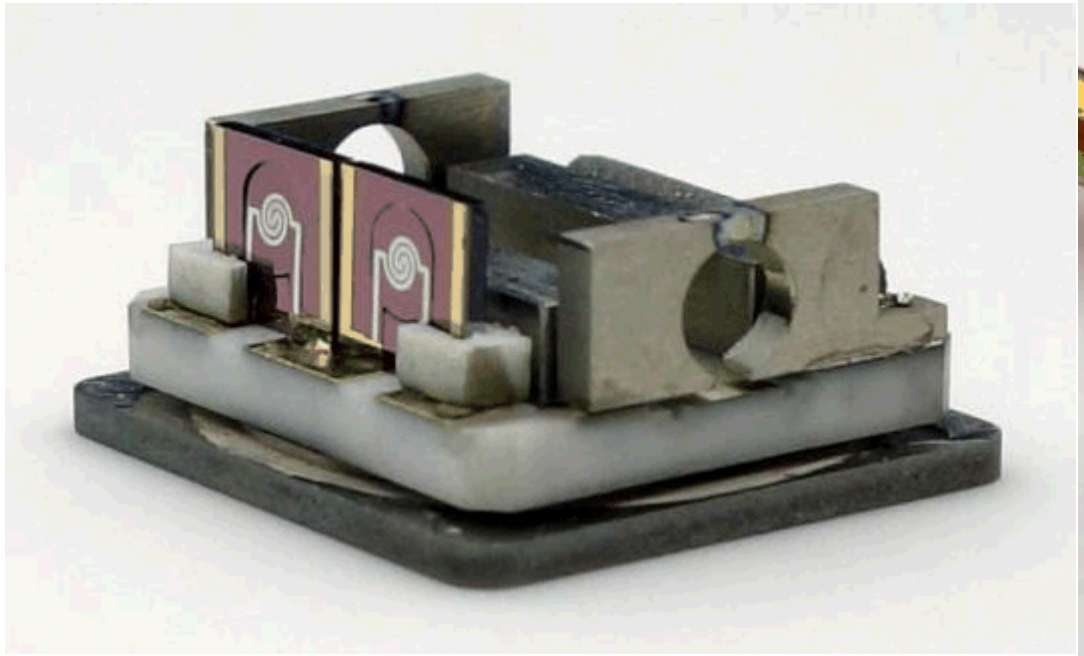
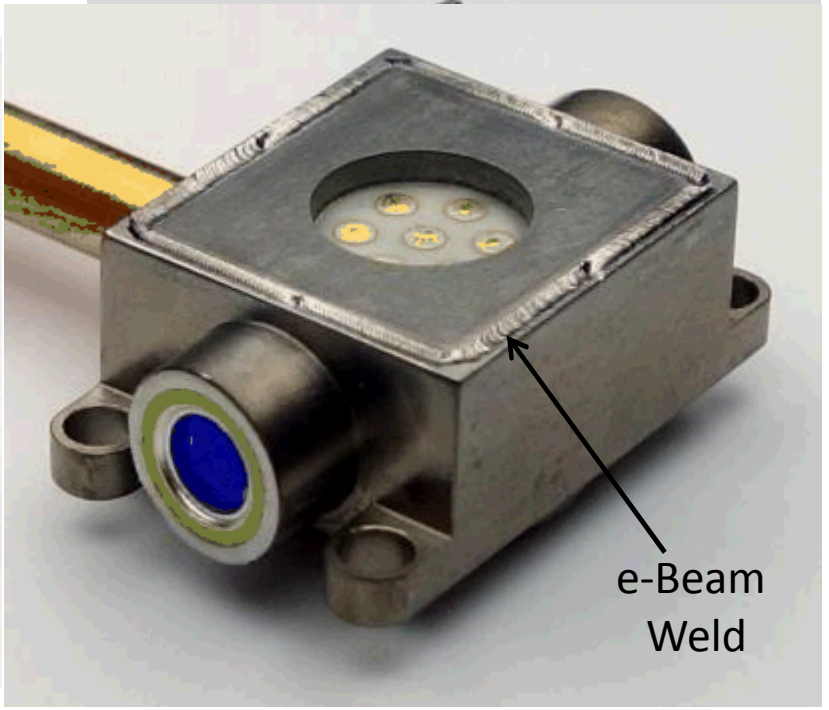
- High temperature co-fired ceramic (HTCC) simplifies the electrical vacuum feedthroughs and internal connections.
- Make the ion trap an integral part of the vacuum package for maximum miniaturization.
- Integrated Yb sources: Silicon micro hotplate
- CuAg braze the Ti parts to the HTCC
- AuGe solder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

Exploded View



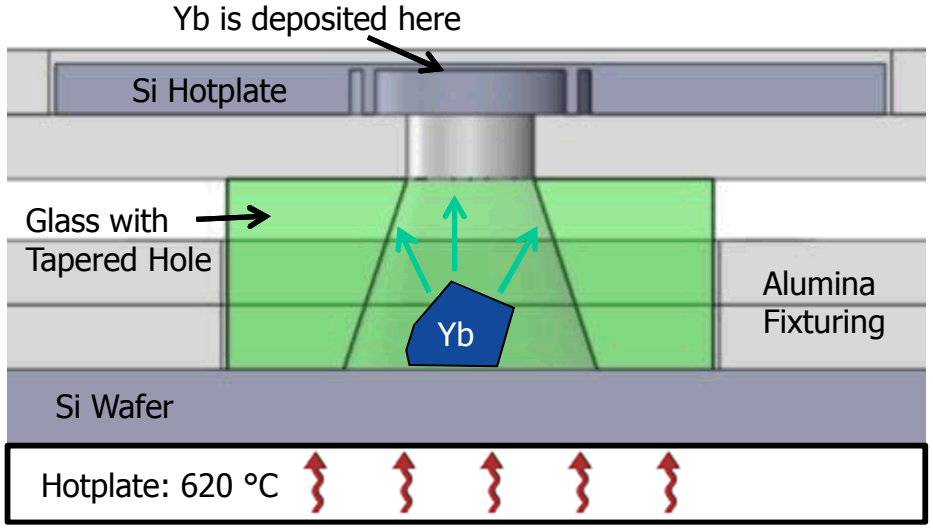


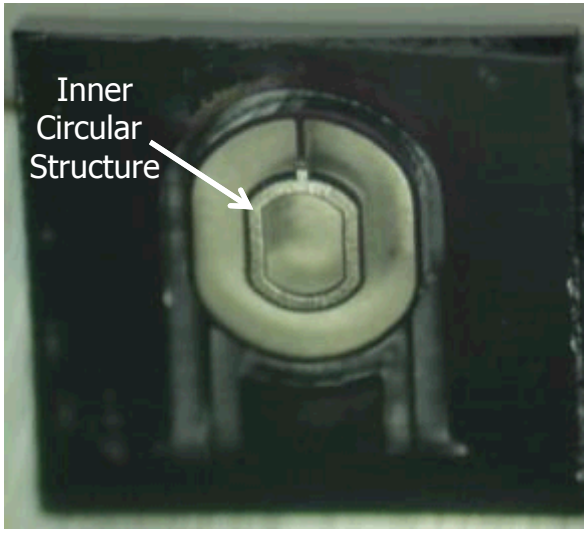


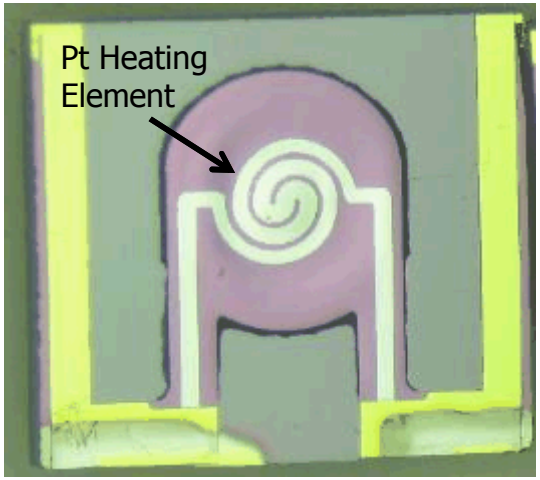
Yb sources: Silicon Micro Hotplate

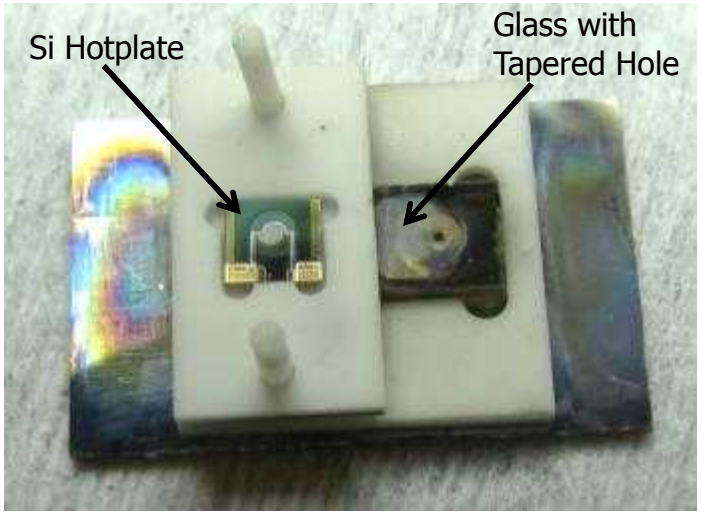
- Evaporate Yb into the Si micro hotplates
- Heat base to 620 °C for 2 hours in vacuum
- 30-50% is deposited into the Si micro hotplate: 0.5-0.8 mg
- Inner circular structure in hotplate prevents CTE mismatch between Yb and Si from cracking the Si.
- Typical power for Yb evaporation: 1.5 V × 0.17 A =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

Yb Deposition Assembly



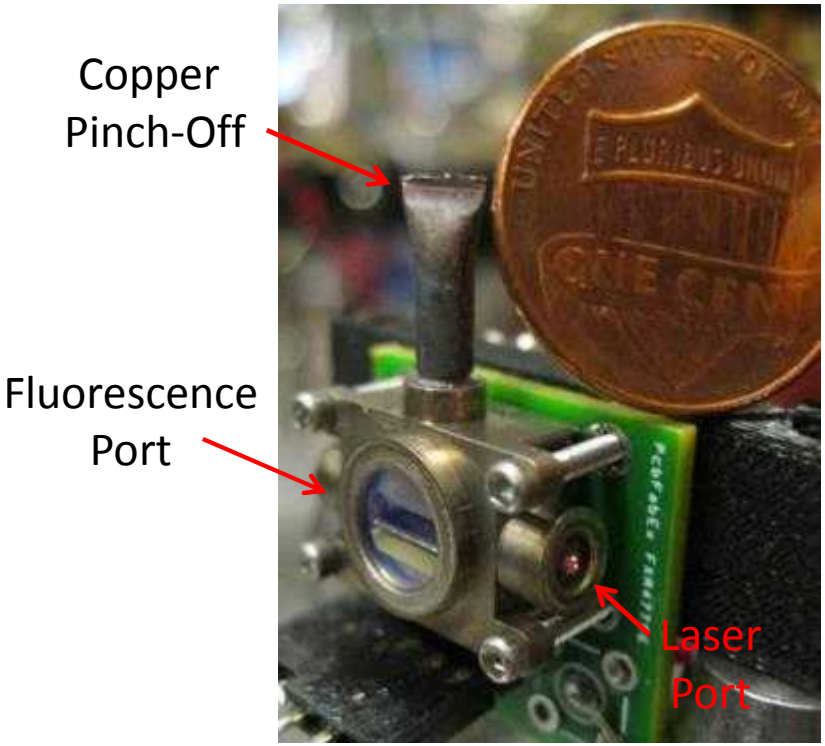


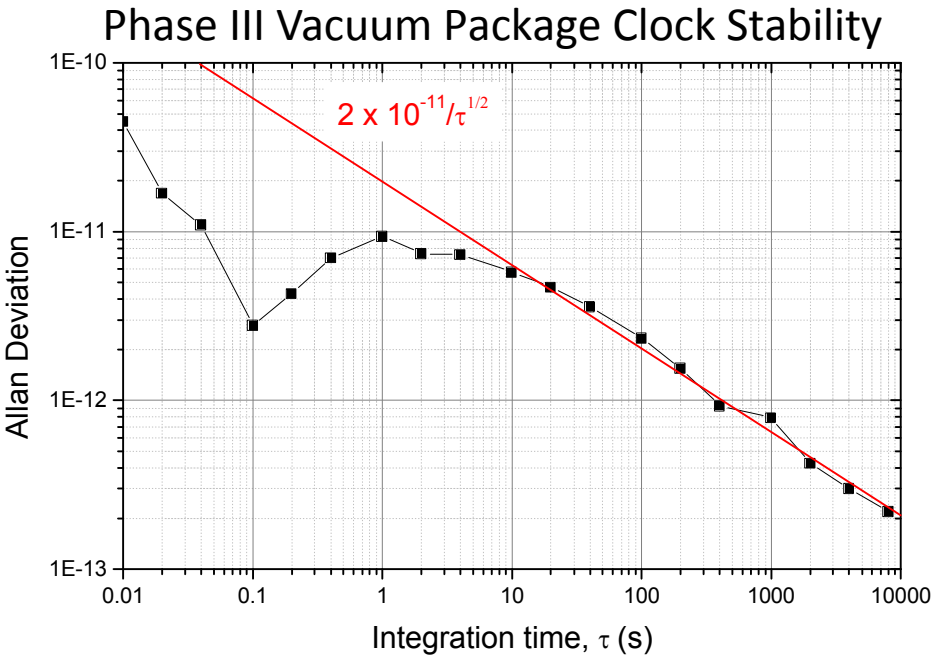


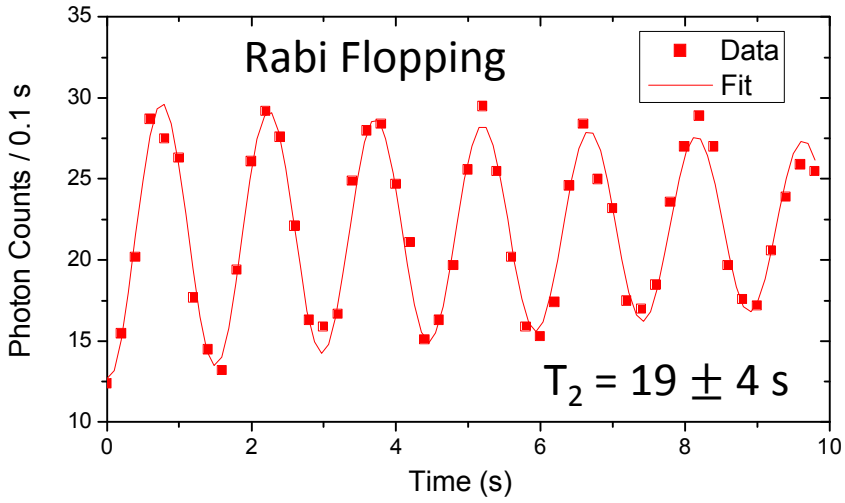


Performance of the Phase III Vacuum Package

- 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

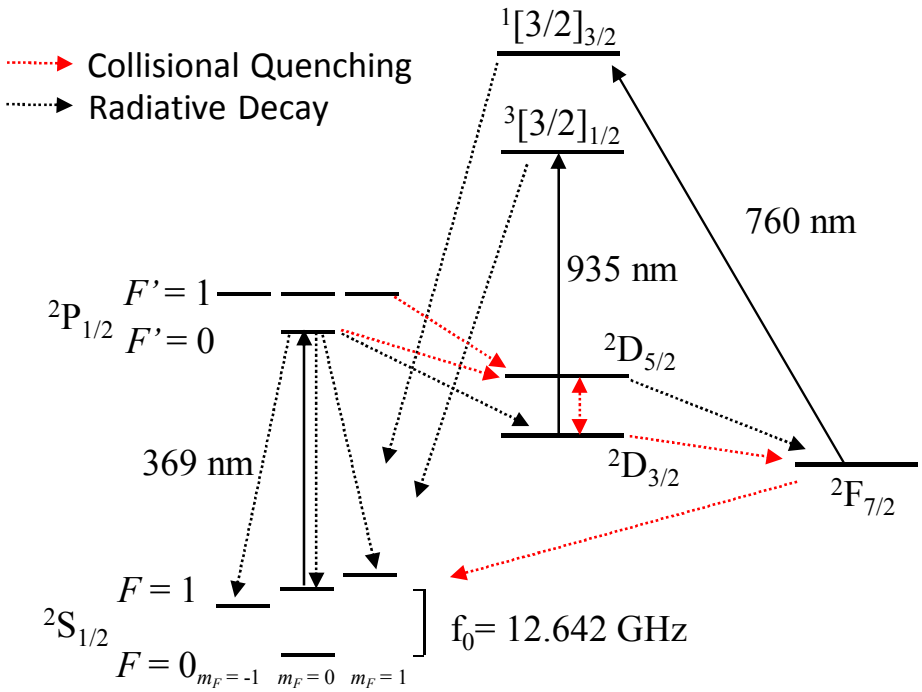


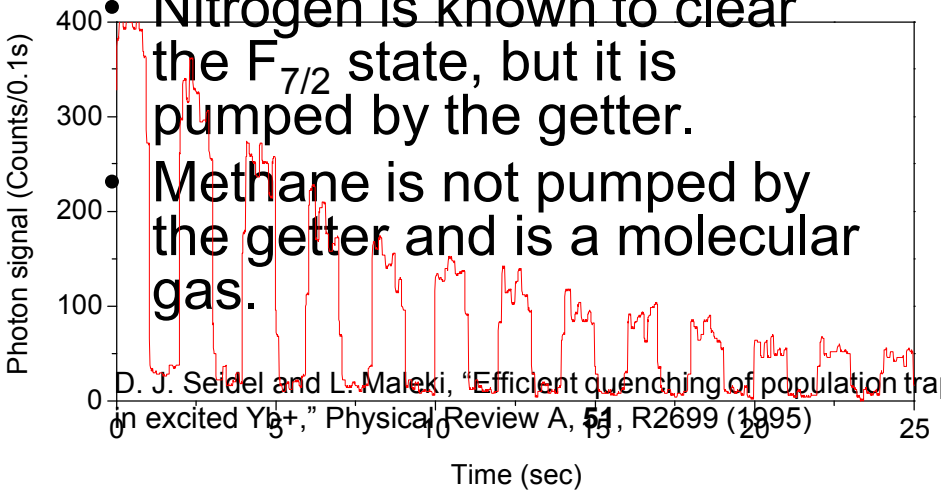




F-State Trapping Problem

- 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.





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

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

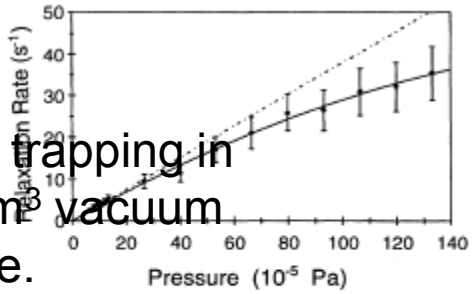


FIG. 3. Quenching rate of ytterbium's trap state vs N_2 buffer-gas pressure. The curved line represents a least-squares fit of the data to the polynomial $\Gamma_{31}=aP+bP^2$; $a=3.63\pm0.12\times10^4$/s Pa and $b=-7.45\pm1.15\times10^6$/s Pa^2, while the straight line represents a linear least-squares fit to pressures $\leq 26.6\times10^{-5}$ Pa.

Testing Methane as a Quenching Gas

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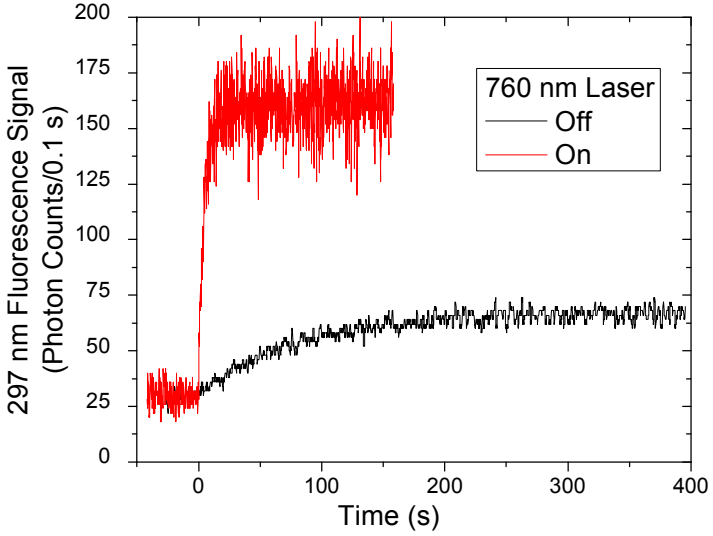
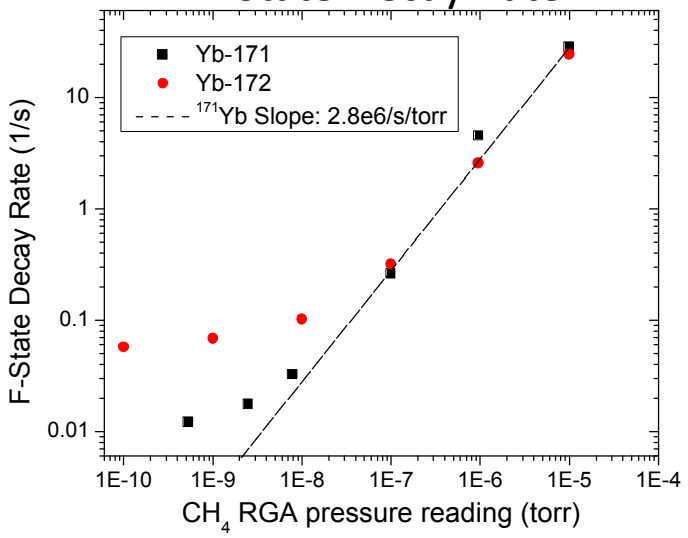
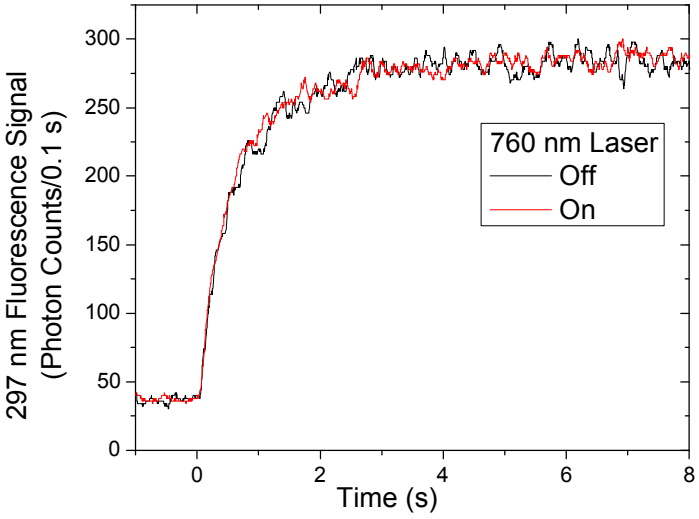
Methane Pressure = 5.3×10^{-10}



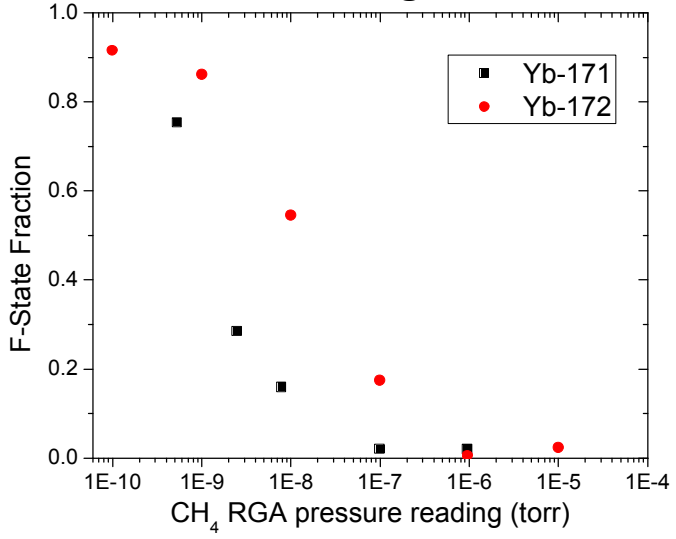
F-State Decay Rate



Methane Pressure = 1×10^{-6}



Fraction Remaining in the F-State

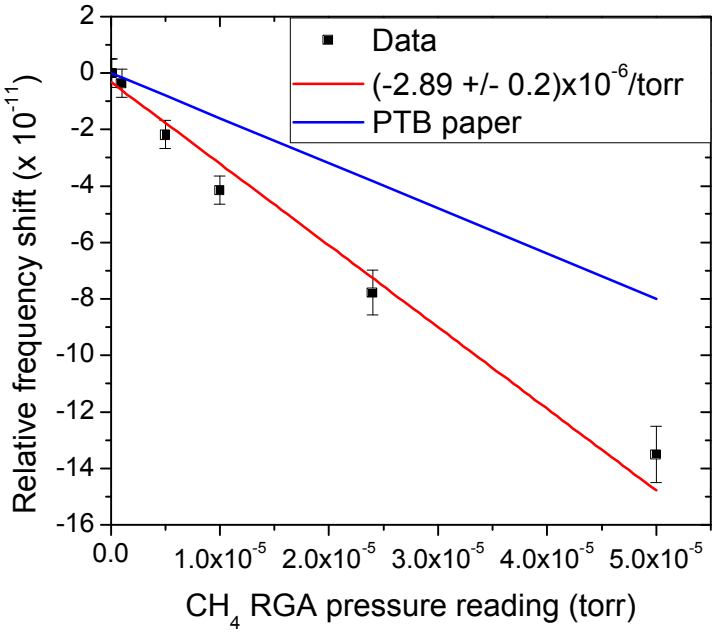


Methane Effects on the Clock State

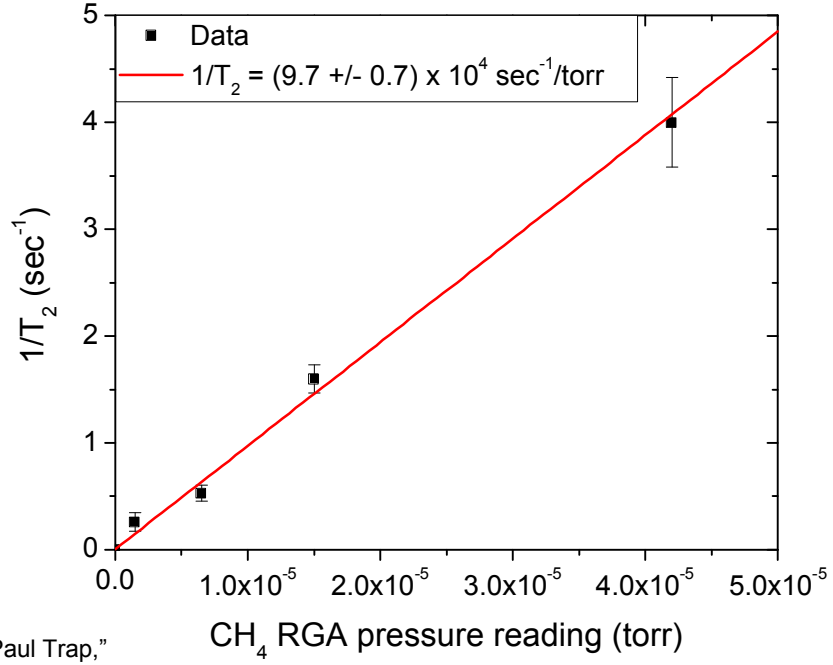
- Estimated methane pressure required for F-State quenching in ^{171}Yb
  - 10^{-8} to 10^{-7} Torr
- F-state Fraction
  - < 20%

- 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



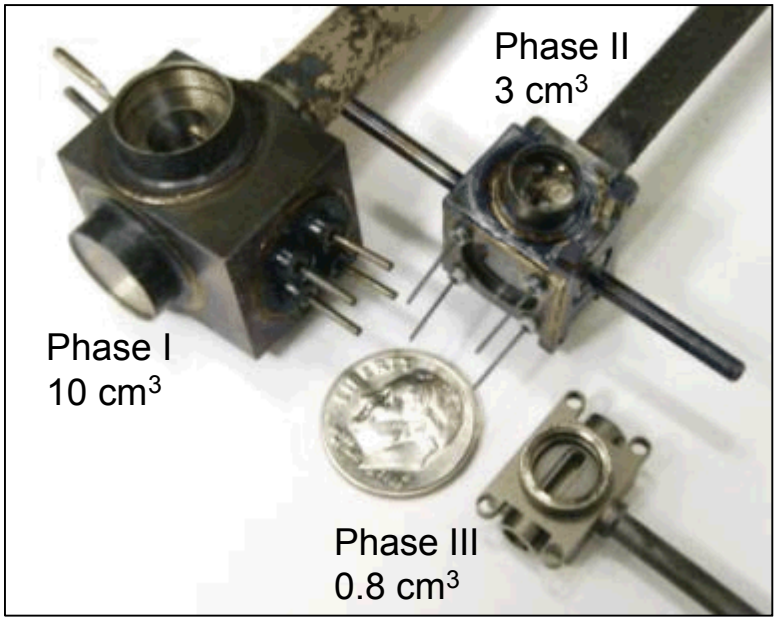
Decoherence Rate in ^{171}Yb Ground State

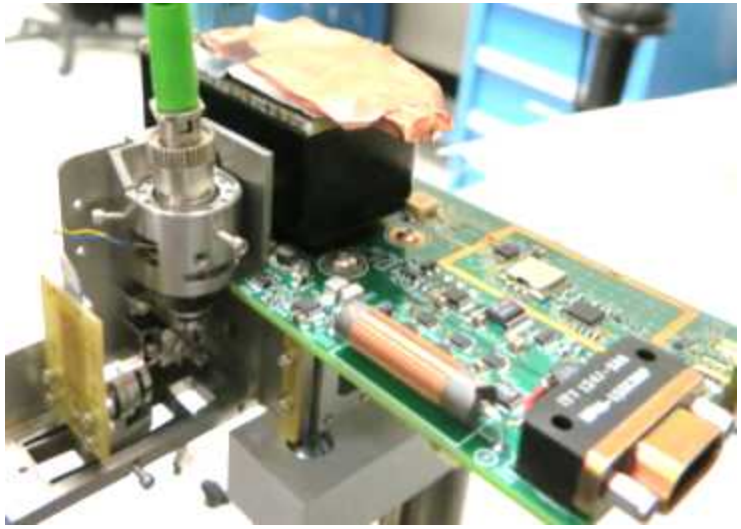


A. Bauch, D. Schnier, and C. Tamm, "Microwave Spectroscopy of 171 Yb+ Stored in a Paul Trap," Proceedings of the 5th Symposium on Frequency Standards and Metrology, pp. 387–388, 1995.

Conclusion

- Developed a clock prototype using the sealed 3 cm3 vacuum package
  - Long-term stability: 6×10^{-14} @ 1 month
- Completed integrated physics package shows $2 \times 10^{-11} / \sqrt{\tau}$
- 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





Back up slides

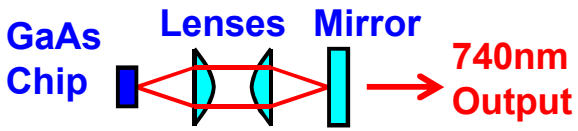
Sandia National Laboratories

369-nm Light Source Development: VECSELs

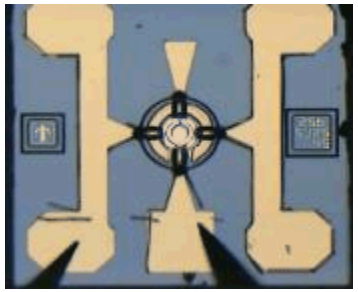
Sandia National Laboratories

- **740nm VECSEL testing**
  - **New implant VECSEL wafer**
    - **15-mm external cavity**
    - **Add filters to suppress high-order modes**

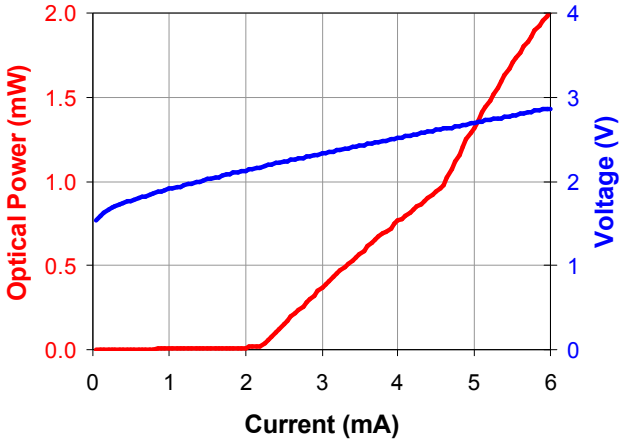
VECSEL Test Setup



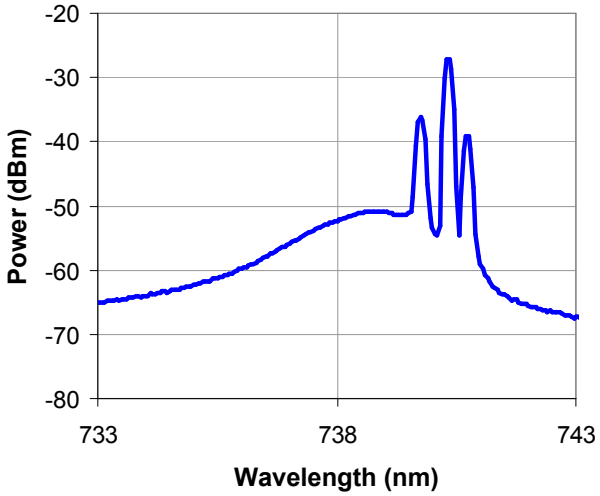
740nm Gain Chip



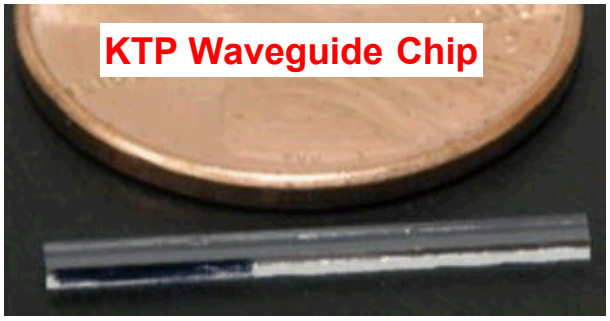
740nm VECSEL Optical Power

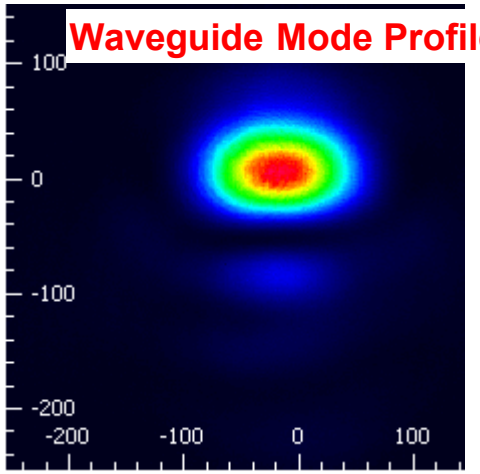


740nm VECSEL Spectrum



- **KTP waveguide characterization**
  - **Measured KTP waveguide mode profile to improve mode-matching efficiency**





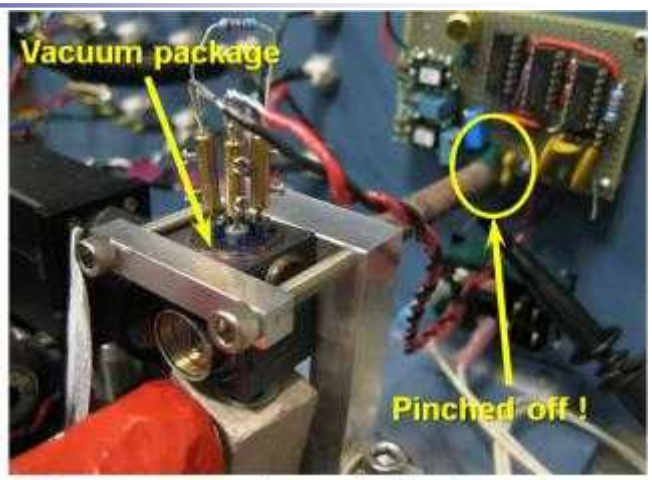
Integrated Micro Primary Atomic Clock Technology (IMPACT) Program Milestones

Sandia National Laboratories

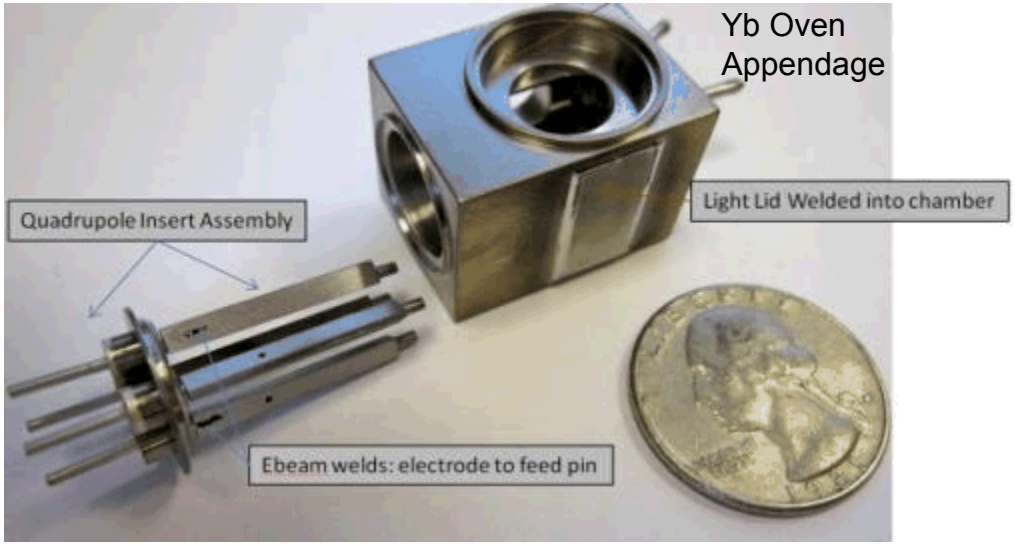
Milestone	Phase I	Phase II	Phase III
Power consumption (mW)	160 (physics package)	250	50
Size (cc)	30 (physics package)	20	5
Atom detector Q*S/N	1×10^{10}	2×10^{10}	5×10^{10}
Time Loss (ns) @ 1 ms	3.2×10^{-3}	1.6×10^{-3}	6.3×10^{-4}
Time Loss (ns) @ 1 s	0.1	0.05	0.02
Time Loss (ns) @ 1 hour	< 60	6	1.2
Time Loss (ns) @ 1 day	< 300	29	5.2
Time Loss (ns) @ 1 month	< 1600	160	32
Fractional Frequency Retrace (1-hour turn on, once every day)	1.7×10^{-11}	1.0×10^{-13}	1.0×10^{-13}

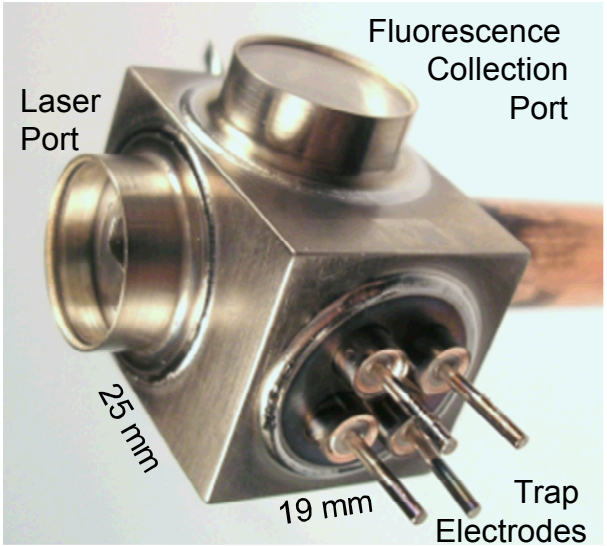
Phase I 10 cm^3 Vacuum Package

- Designed, fabricated, two 10 cm^3 vacuum physics packages
  - The trap is integrated in to the walls of the trap to allow a smaller package.
  - 400 C bake/de-gassing, getter pumped
  - Pinched off since April 4th 2011, no active pumping.
    - Trapped ion lifetime > 500 hours.



10 c.c. package in a portable demo box





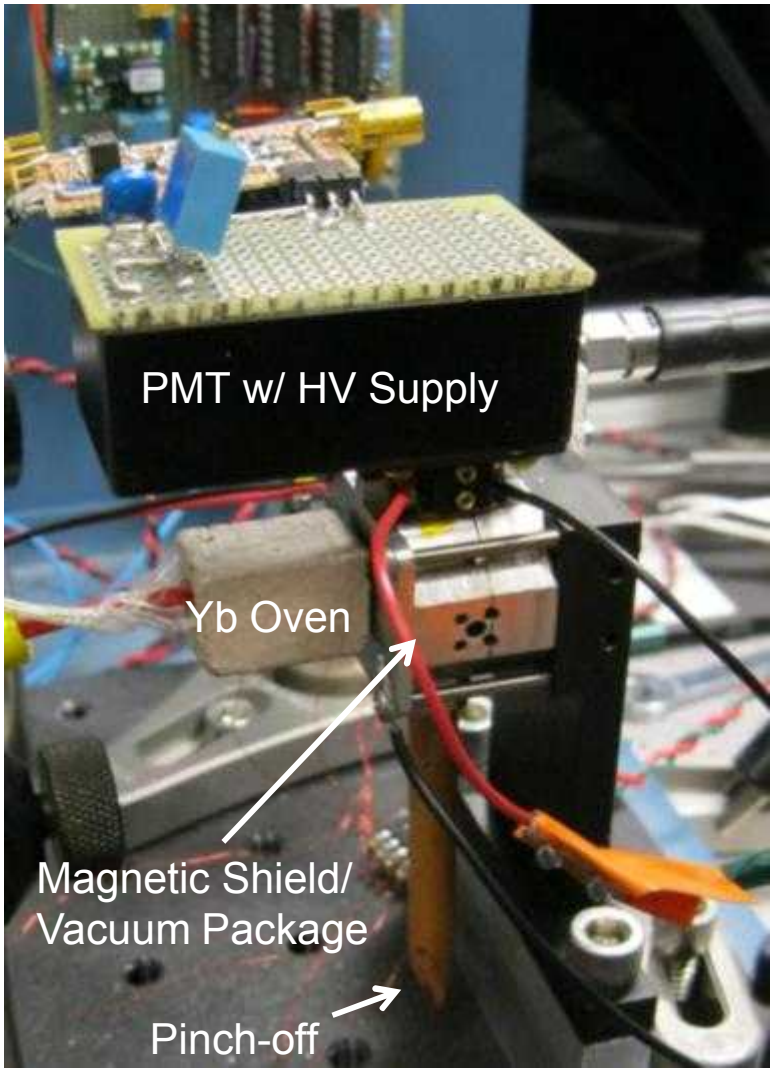
JPL phase II package summary

Sandia National Laboratories

Compact experimental setup

- Trapped ion lifetime of days, and the lifetime is increasing with time
- Volume is approximately 3 cubic cm
- No active vacuum pump is required
- RF drive consumes 20 mW (1.8MHz, 160 Vrf)
- Signals are detected at 297 nm by using the low-power compact PMT + Amp.
- The ions are loaded using 405 nm laser diode.
- All nonmagnetic materials, 400C bake temperature (>600 C survival)
- Design integrates coils and magnetic shield
- Compact 935 nm VCSEL control electronics developed by Symmetricom

935 VCSEL optical power 0.4 mW
369 nm optical power thru trap: 20 uW

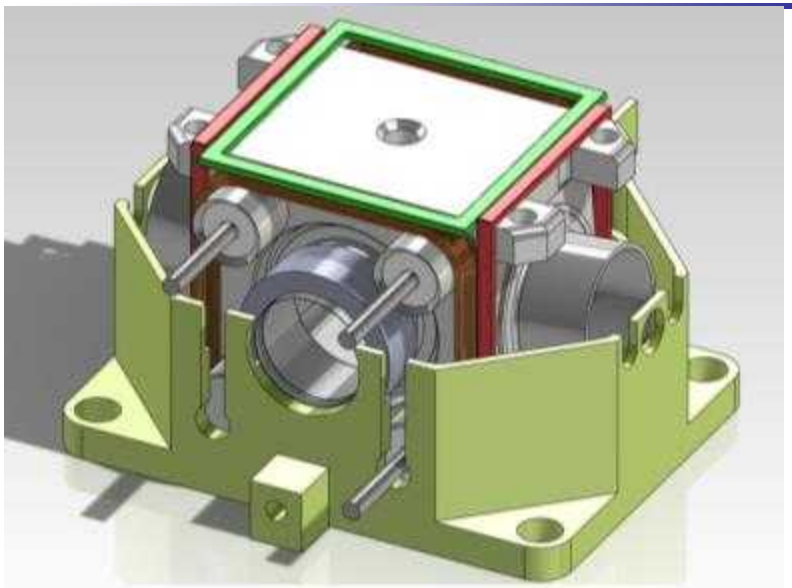


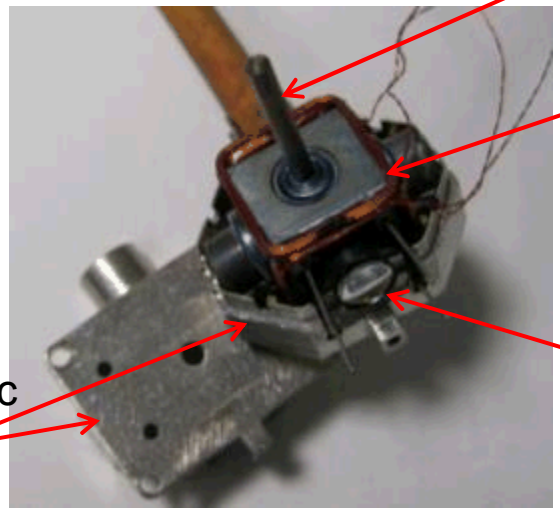
JPL Jet Propulsion Laboratory California Institute of Technology

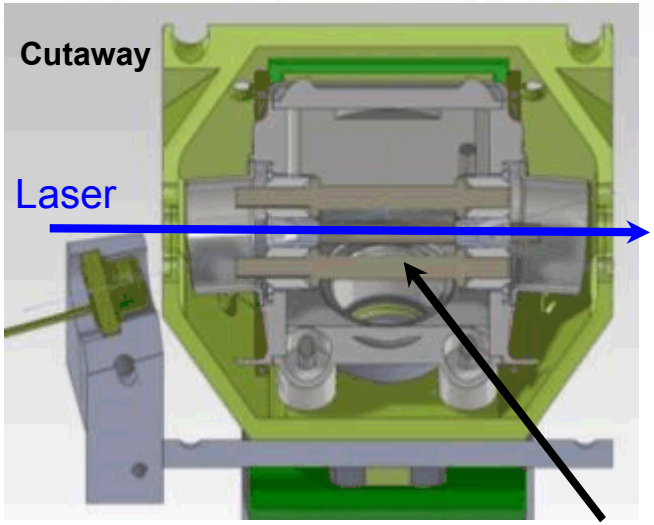
Sandia National Laboratories

Phase II 3 cm^3 metal package

Sandia National Laboratories







For demonstration of a complete portable clock

Smaller sealed Titanium package - all nonmagnetic materials

Incorporates shield and field coils to control magnetic field fluctuations which are one of our limiting factors for long-term performance

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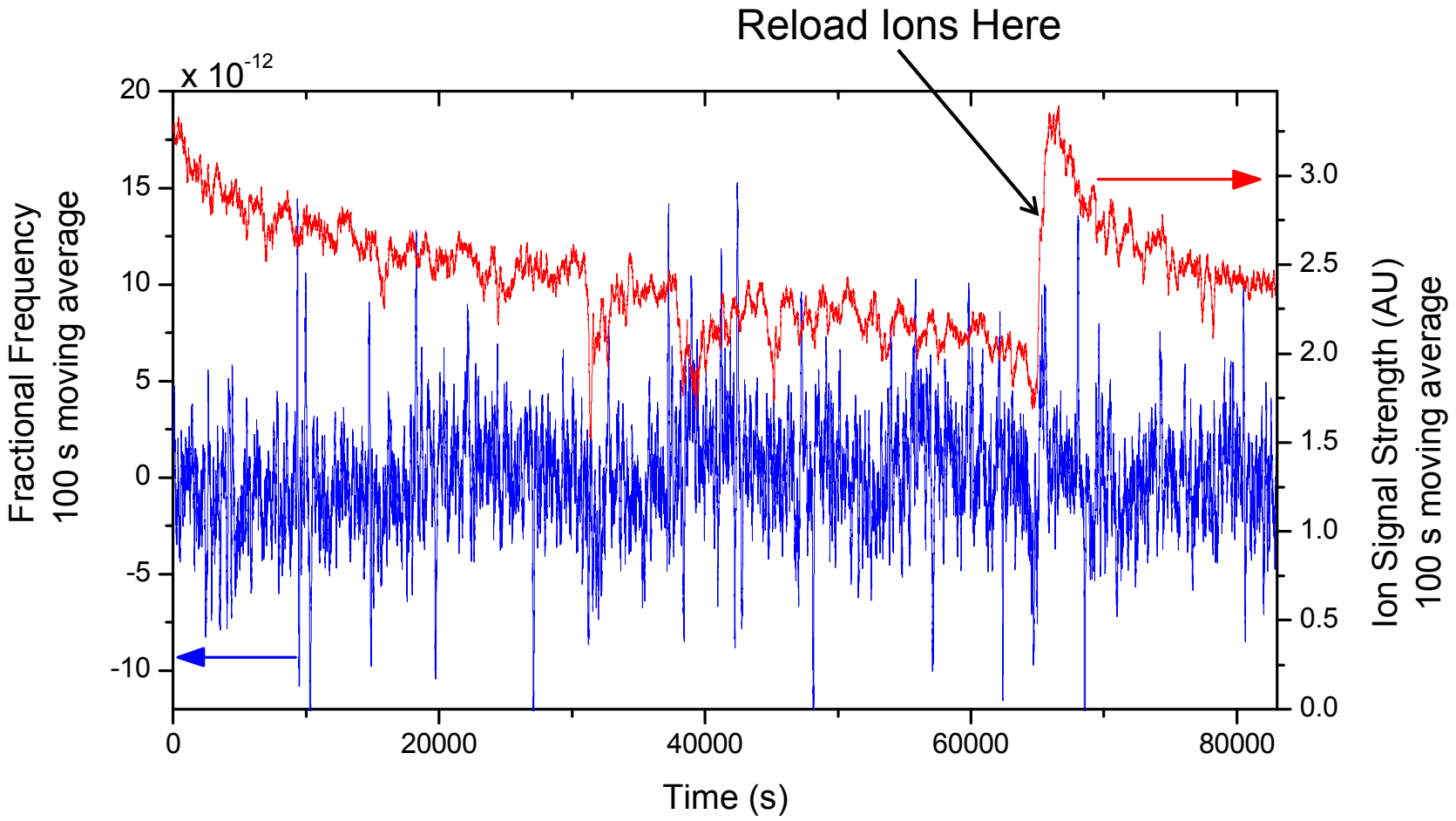
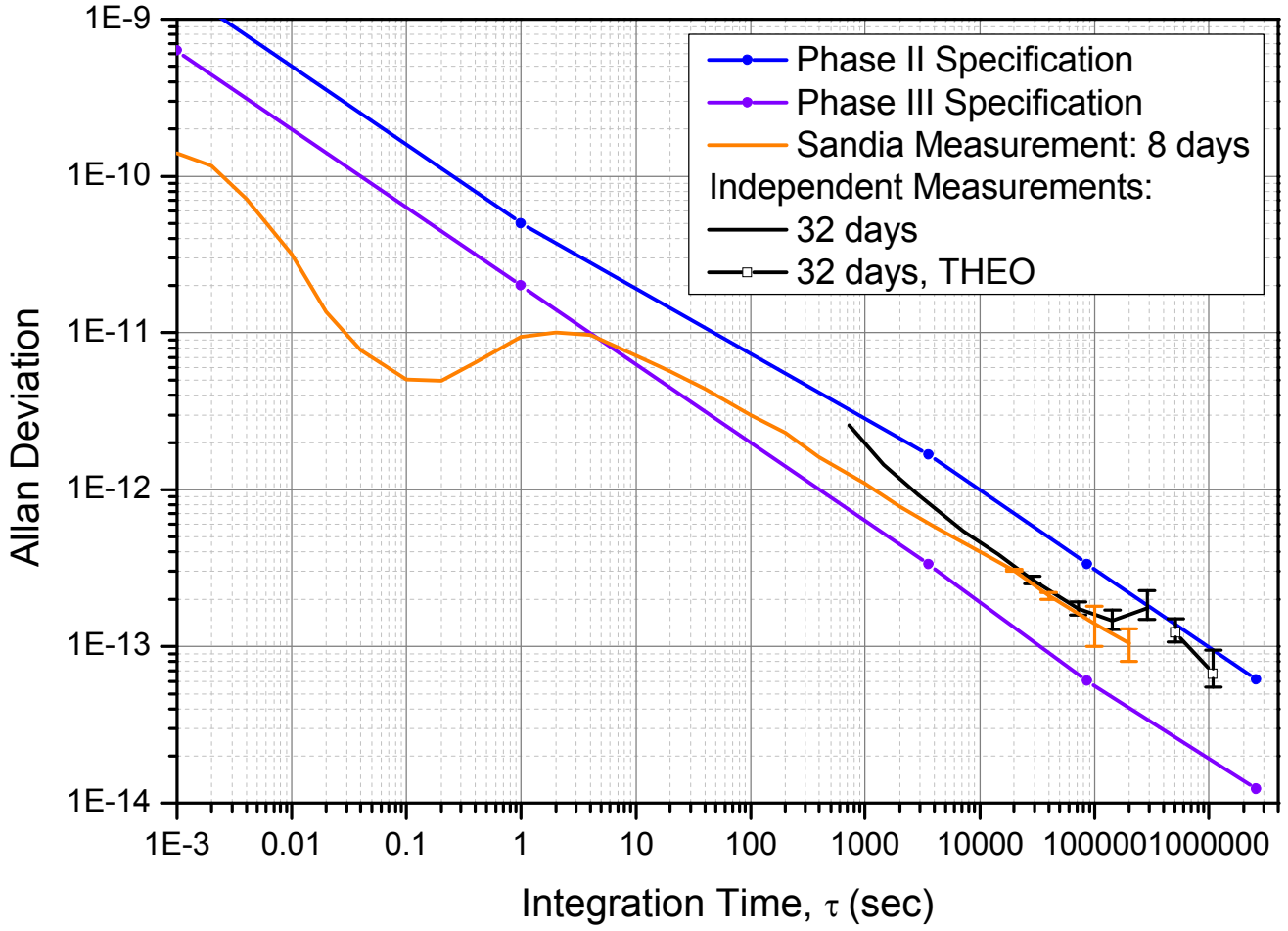
Continuous Operation with Ion Reloading



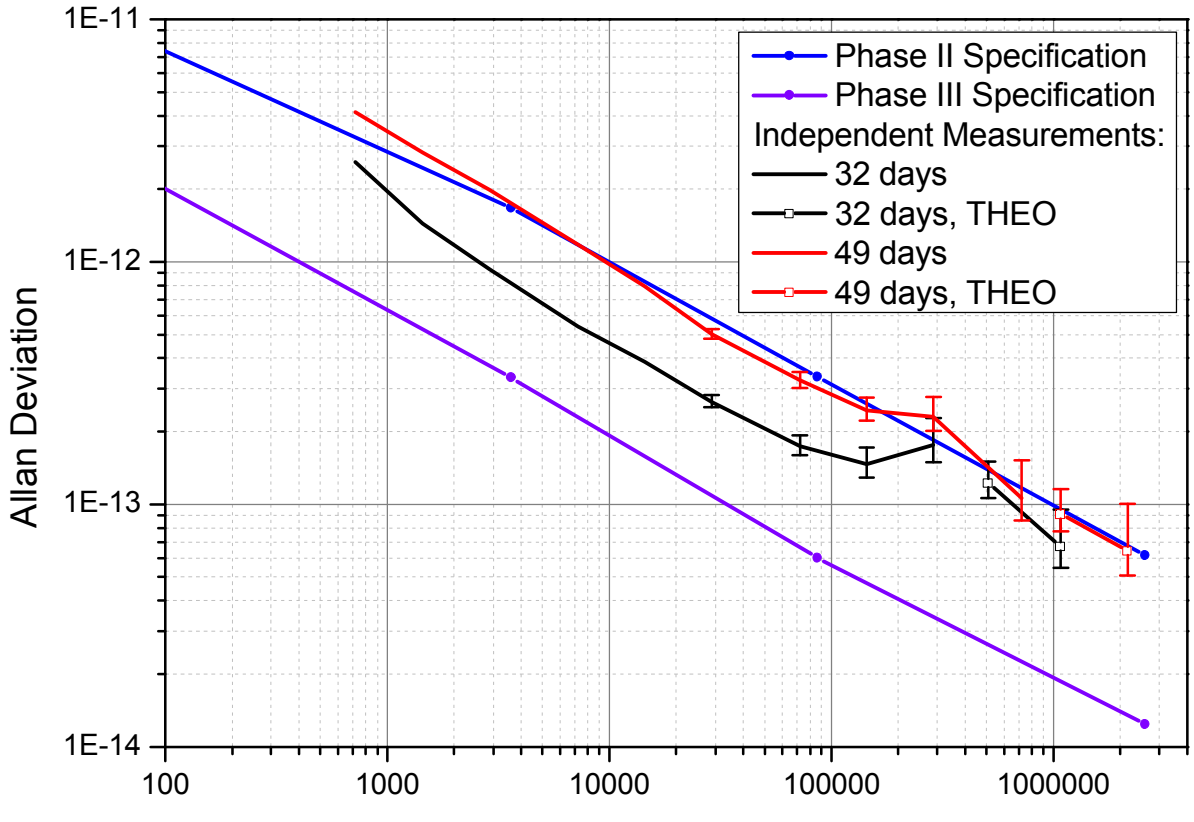
Clock Performance

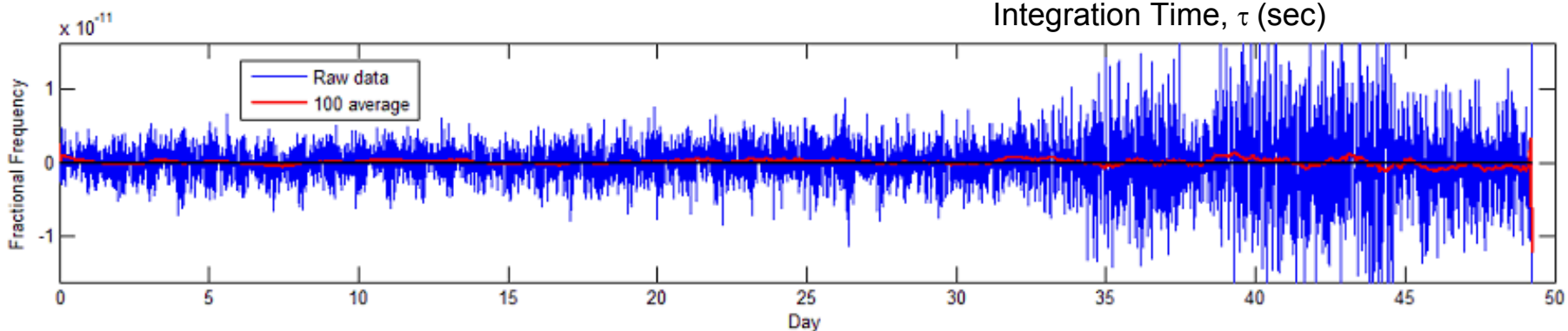
- Operate physics package with Symmetricom developed control electronics.
- Local oscillator: 10 MHz OCXO: 60 mW
- 12.6 GHz microwaves phase locked to OCXO.
- Clock cycle = 500 ms
  - Microwave = 200 ms
  - Detection/Optical Pumping = 300 ms



Independent Testing

- Delivered the clock to test facility in late June 2012
- Demonstrated 31 days of continuous operation, 49 days of data collected
- Allan deviation derived from data sets of 6 days, 26 days, 3 days, 4 days, and 10 days. Phase steps removed.
- Frequency reproducibility between data sets: 2×10^{-13}

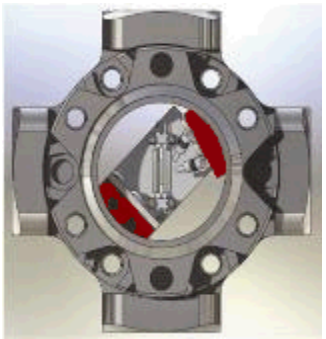




Evolution of the Vacuum/Trap Packages

Sandia National Laboratories

Phase-I 1-liter package for proving the operation of the mini-ion-trap.



Sealed off
Getter pumped

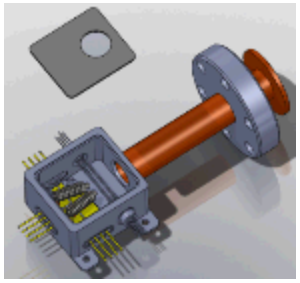
Demonstrated trapped ion lifetime > 600 hrs.

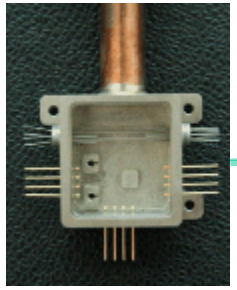
Phase-I 18 c.c. package for proving the feasibility of small vacuum volume.

Sealed off
Getter pumped

Demonstrated trapped ion lifetime > 100 hrs.

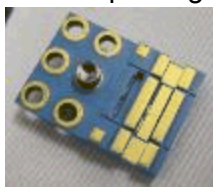
Phase-I Sandia designed 10 c.c. vacuum package. Pinched off, getter pumped .

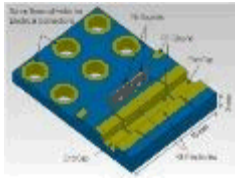


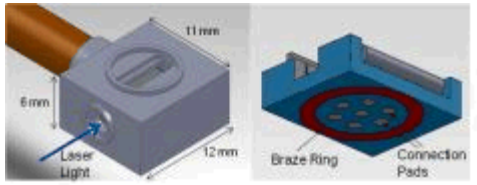


Demonstrated trapped ion lifetime > 500 hrs.

Phase-II 1 c.c. Sandia developed ceramic package.

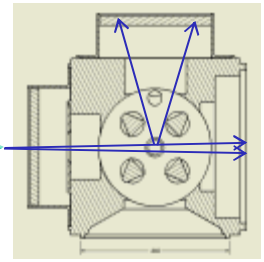


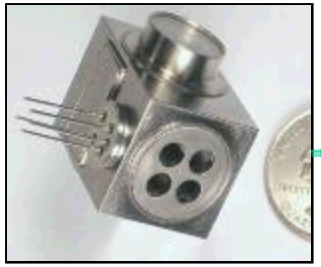




Demonstrated long-term ion trapping.

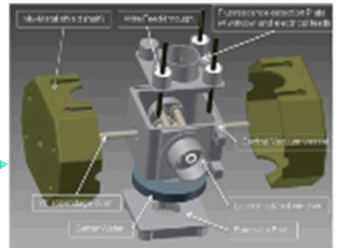
Phase-I JPL designed 10 c.c. vacuum package. Pinched off, getter pumped, electron emitter.





Demonstrated trapped ion lifetime > 1000 hrs.

Phase-II JPL designed 3 c.c. vacuum package.



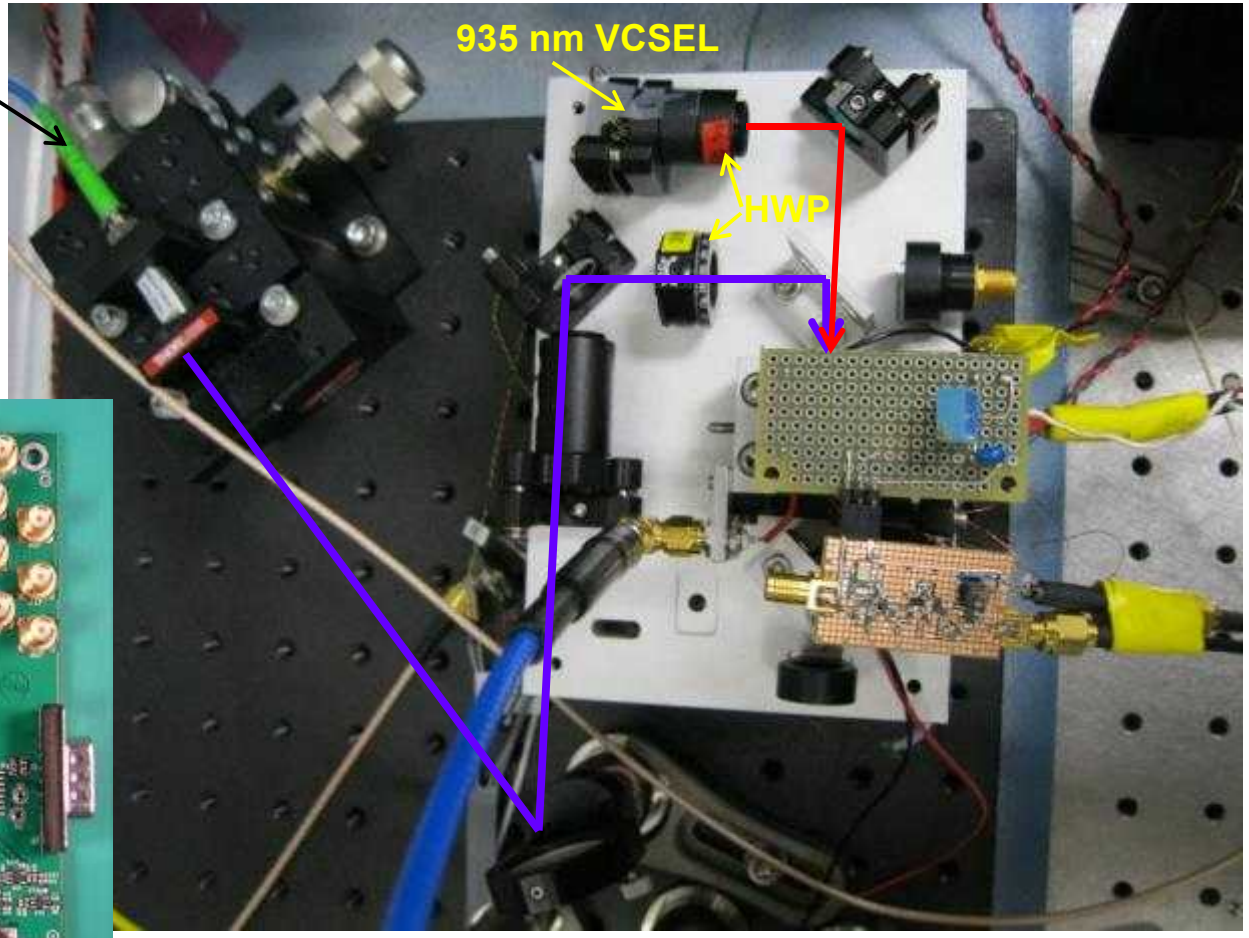
JPL Jet Propulsion Laboratory California Institute of Technology

Sandia National Laboratories

Phase II Clock Prototype

Sandia National Laboratories

Physics Package



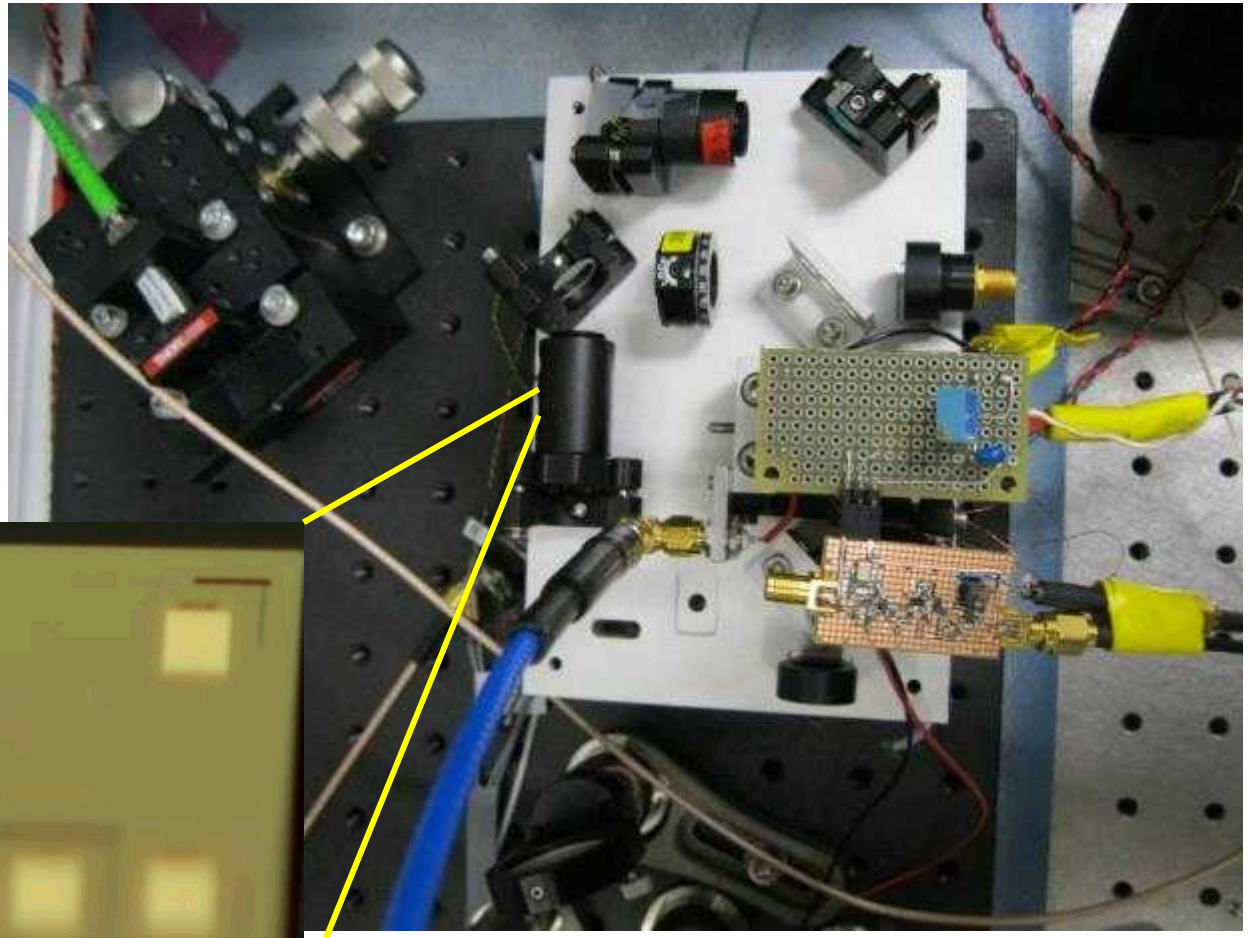
Fiber from
369 nm Laser

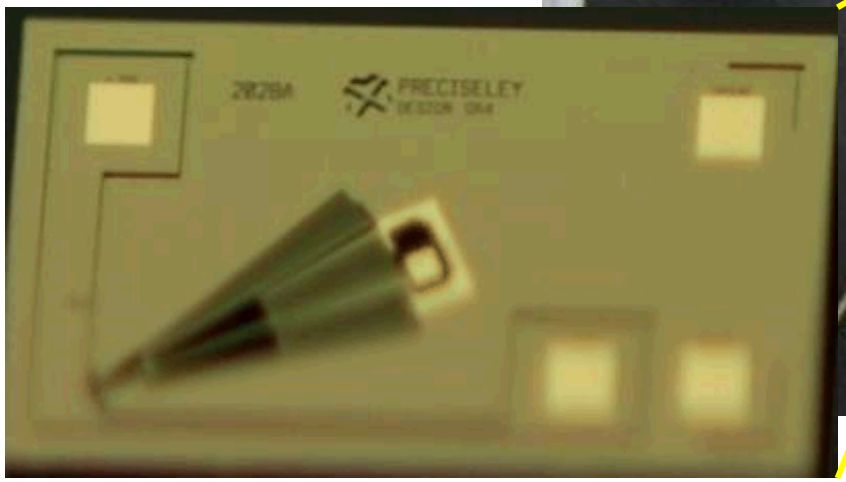
Symmetricom Electronics

MEMS Shutter

- Small moving blade
  - 60 μm throw
- Mounted with 50 μm pinhole above the blade
- Requires 20-25 V to activate.
- Extinction > 40 dB
- 10-90 Switch time
  - On: 47 μs
  - Off: 62 μs

Physics Package





Integrated Vacuum Package, Magnetic shield, Yb oven, and Detector

Sandia National Laboratories

- Signals are detected at 297 nm by using the low-power compact PMT + Amplifier.
- Yb oven heats Yb metal to create a vapor at 450-500 C.
- Blu Ray burner diode at 405 nm to creates ions.