Small Mercury Ion Clock for On-board Spacecraft Navigation*

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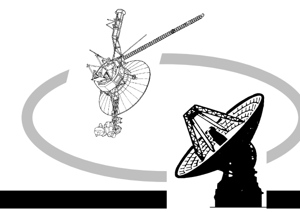
Outline

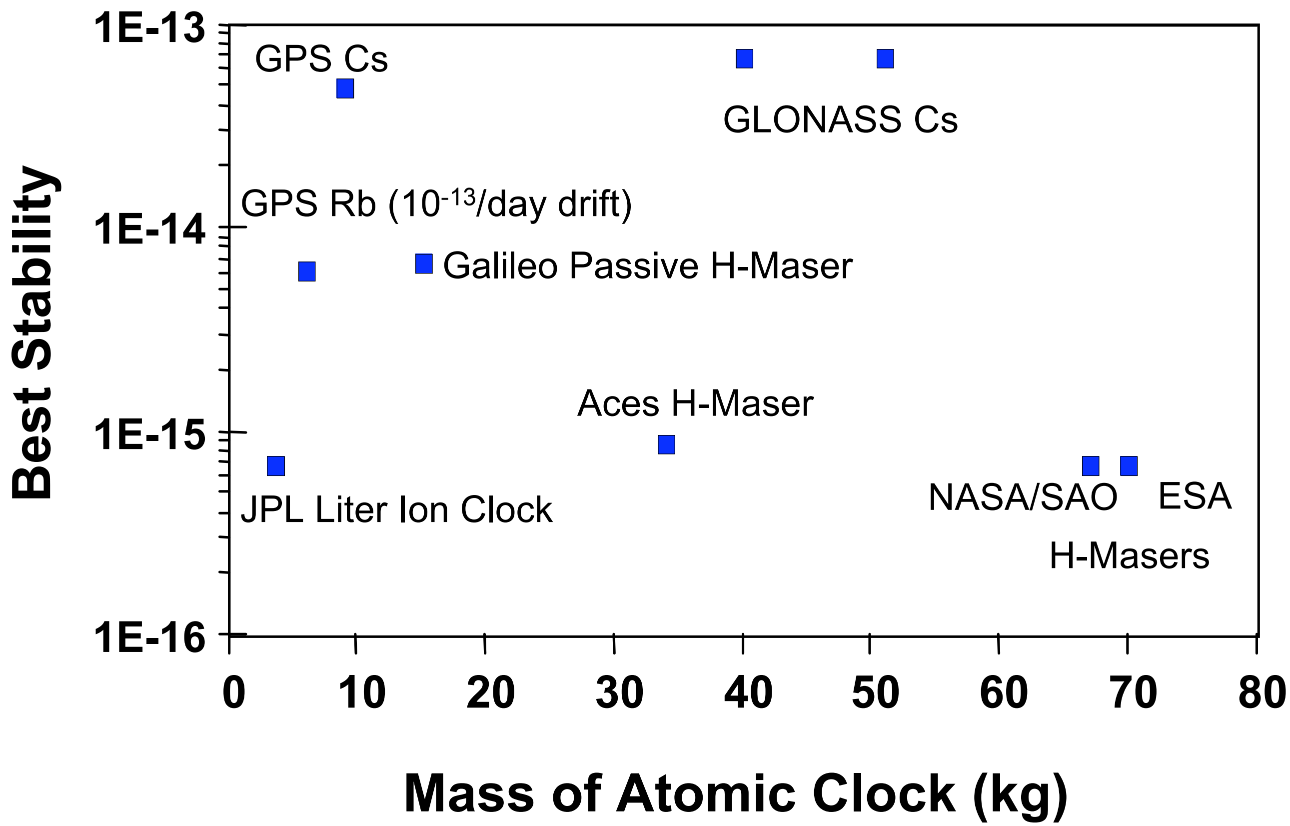
- Review of Ultra-Stable Space clock Mass vs Stability
- Laboratory Hg microwave Ion clock
  - Ion shuttling from 'Optical' trap to Microwave resonance trap;
  - 3×10^{-16} 'floor' with > 100x less drift than space Rb;
- Development of a One-Liter Hg Ion clock
  - Optical System Re-design;
  - Trap miniaturization, one piece brazed, no fasteners,…
  - Ultra-high Vacuum developed for getter pumping;
- Tests of Breadboard Liter clock Package
  - 5×10^{-14} at 1 second;
  - 3x reduction buffer gas shift with Neon
- Summary

Small Mercury Ion Clock for On-board Spacecraft Navigation



- JPL can use a small, reliable, high stability clock, ~10^{-14} to 10^{-15} for deep space navigation
- Interplanetary S/C radio system components (TWTA, USO,..) are 1-2 kg /2-3 liters

Space-Based Clocks (LEO)

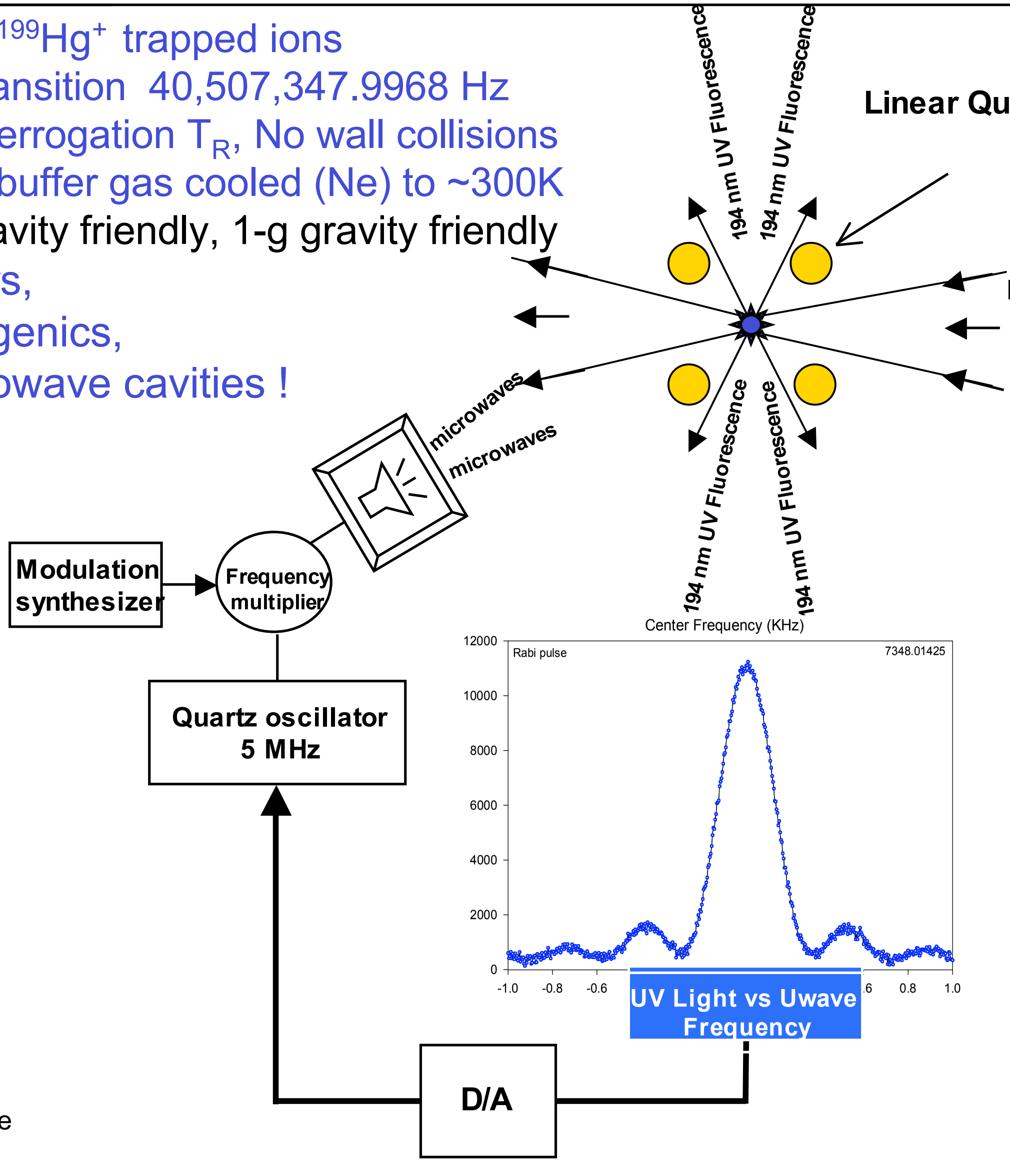


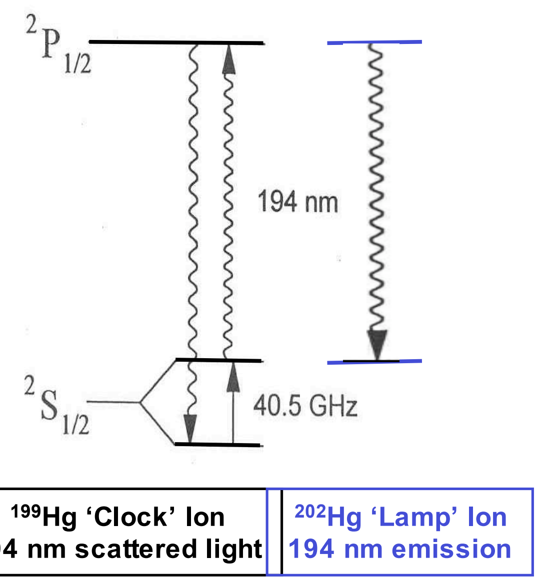
How Large are Deep Space Craft ?

Voyager I	< 825 kg
Magellan (1989)	1035 kg
Ulysses (1990)	370 kg
Mars Observer ☹	1018 kg
Mars Global Surveyor	674 kg
Mars Pathfinder	570 kg
Cassini (1997)	2580 kg
Deep Space 1	373 kg
Mars Climate Orbiter ☹	388 kg
Stardust (1999)	300 kg
Mars Odyssey	376 kg
MER (Rover 185kg)	1013 kg (rover + s/c)

Why/How a Clock from Ions ?

- 10^6-10^7 $^{199}Hg^+$ trapped ions
- Clock Transition 40,507,347.9968 Hz
- Long Interrogation T_R, No wall collisions
- Ions are buffer gas cooled (Ne) to ~300K
- Micro-gravity friendly, 1-g gravity friendly
- No lasers,
- No cryogenics,
- No microwave cavities !





- Optical Pumping: 194 nm UV
- $^{202}Hg^+$ RF discharge lamp
- Q~3×10^{11} resonance measured thru UV fluorescence

Over-view of Multi-pole Clock (1st design)

No Lasers, Microwave Cavities, or Cryogenics

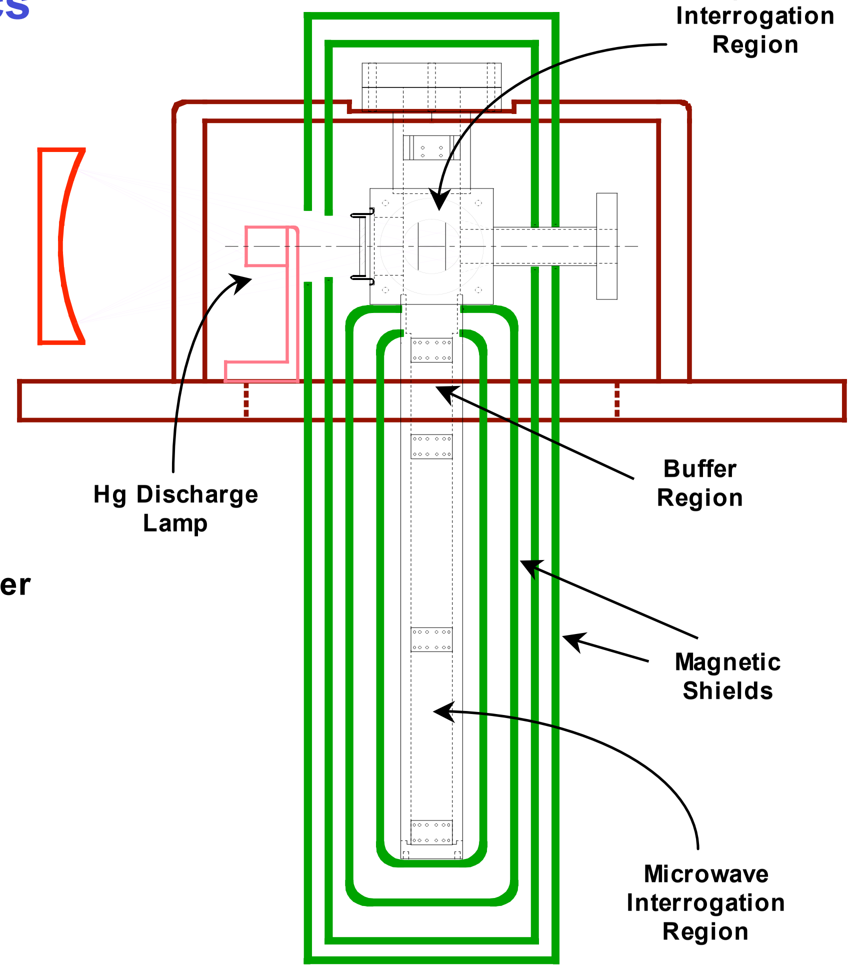
~20 years operational experience in 5 clocks,
- 3 linear traps,
- 2 shuttle from linear 4-pole to multi-pole
- All exceed 10^{-15} stability

Ions are Optically Pumped in a quadrupole trap
(optically open and ions are concentrated)

40 Ghz Clock resonance in Multi-Pole trap, an RF trap with little or no radio frequency micromotion
(low ion density, low micro-motion, little space-charge number sensitivity)

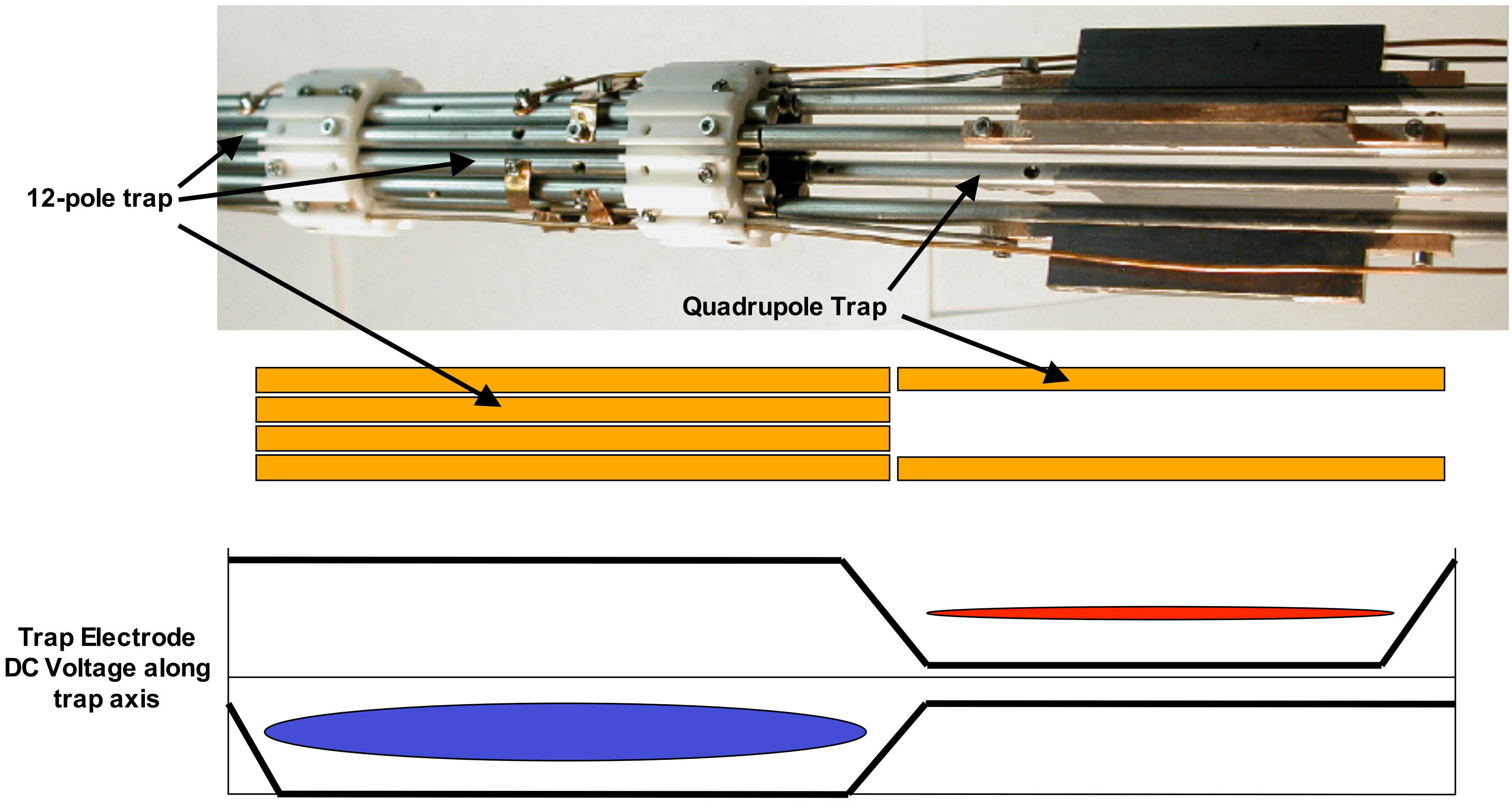
- Doppler-free for transverse k vector
- Doppler broadened for axial k vector

Ions are shuttled between 4-pole and 12-pole



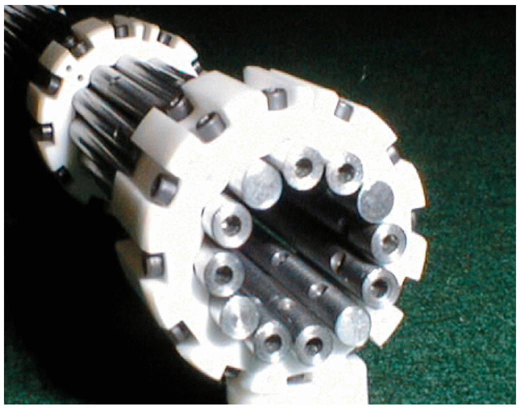
Hg Ion Frequency Standard

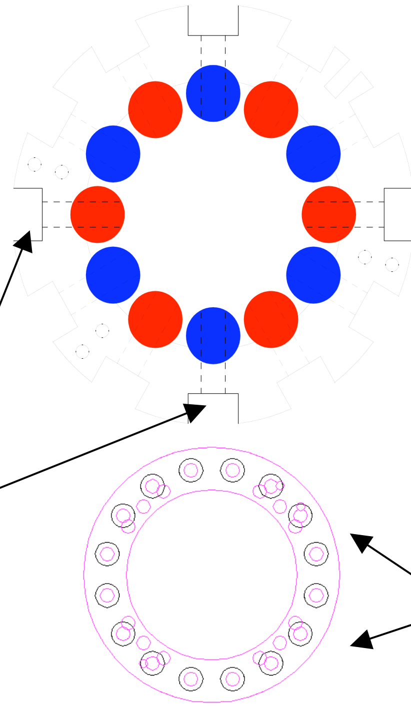
Shuttling Ions from Quadrupole to 12-Pole (and back)



~5,000,000 shuttles have been executed to date in USNO unit

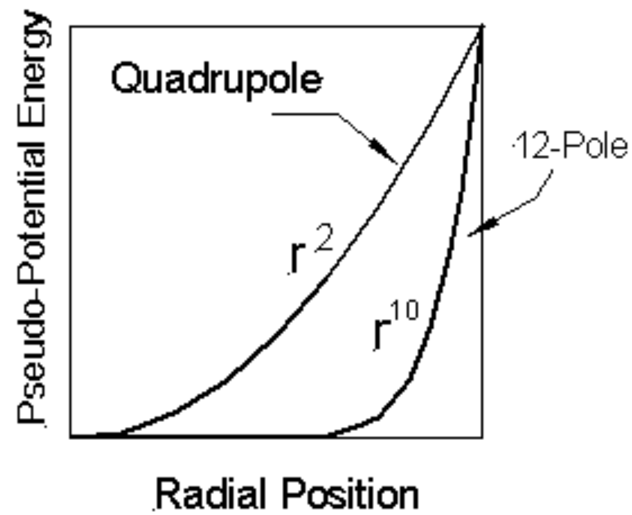
Quadrupole vs Higher Pole
(RF trap with little micro-motion in microwave region)





Laboratory 12-pole

Space-clock 16-pole
60% external diameter
100% internal diameter



Pseudo-potential grows as R^{2k-2} for 2k rod electrodes

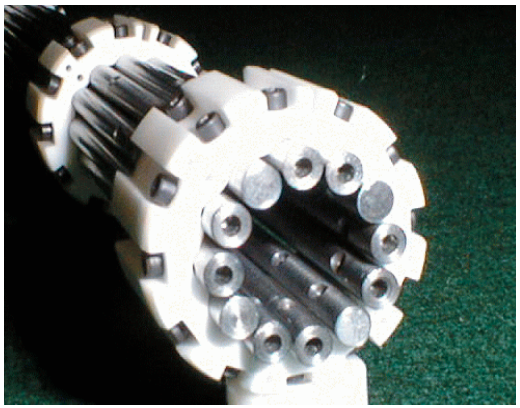
$$U_{pseudo} \propto R^{2k-2} \qquad \overline{KE}_{transverse} = (k-1)\overline{U}_{pseudo}$$

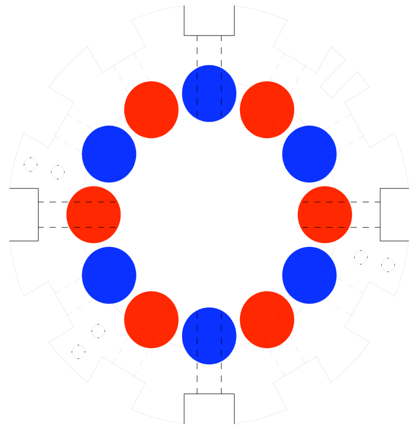
(Virial Theorem)

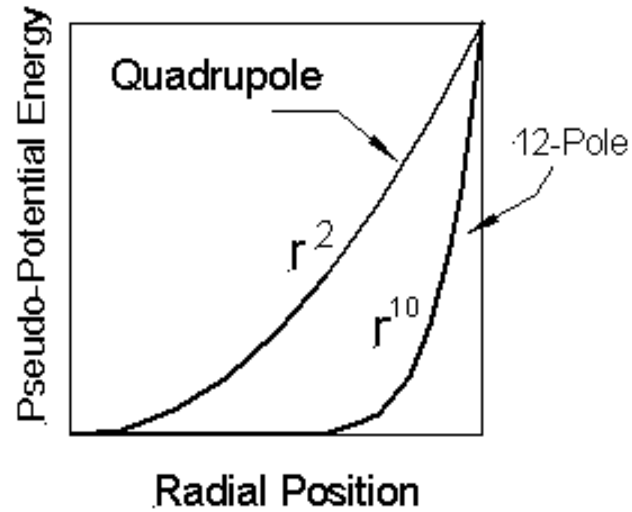
$$\overline{KE}_{m-motion} = \overline{U}_{pseudo} = \overline{KE}_{tranverse} \Big/ (k-1)$$

RF Trap with very little RF micro-motion (k=2 quadrupole)

Quadrupole vs Higher Pole (Well Depth)







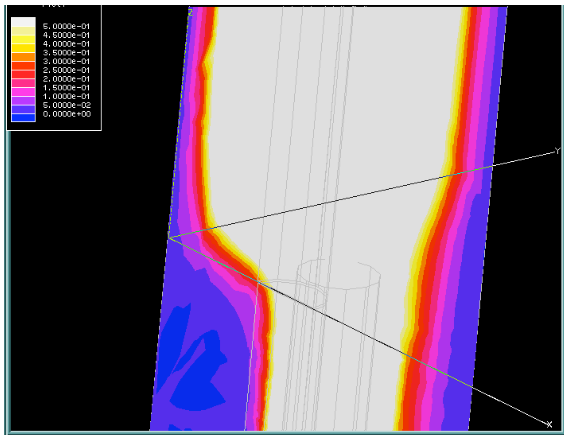
$$\eta = \frac{2q\left|\nabla E_0\right|}{m\Omega^2} = k(k-1)\frac{qU_0}{m\Omega^2 r_0^{\ 2}}\hat{r}^{k-2} \le 0.3 \equiv \eta_{max}$$

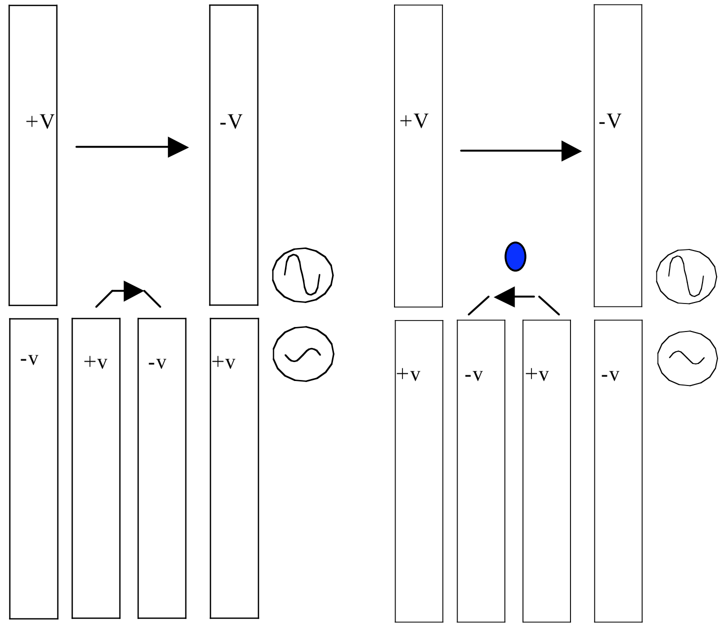
Numerical trajectory;D. Gerlich, Adv. Chem. Phys. LXXXII (1992)

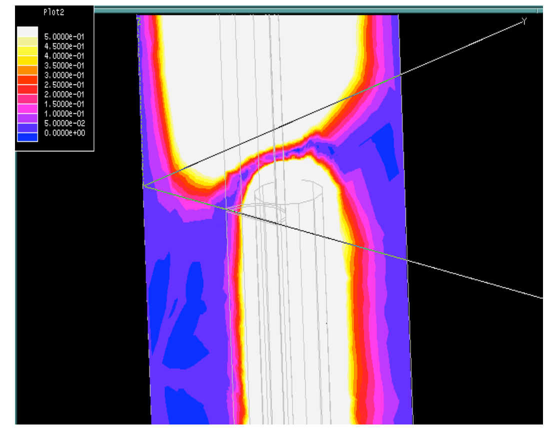
$$V^*_{k>>1}(R_{max}) = \frac{m\Omega^2 r_0^{\ 2}}{k^2}\frac{\eta_{max}^{\ \ 2}}{16}$$

Well depth diminishes with k^2 unless frequency, Ω, increases with k

Shuttling Ions from Quadrupole to 12-Pole (phase must change on co-linear rods at trap junction)







Opposite Phase on colinear electrodes produces good RF pseudopotential

Same Phase on colinear electrodes produces a hole in the RF pseudopotential

- **Problem: Joining a 4-pole to an arbitrary k-pole microwave resonance trap. Holes in the pseudo-potential cannot be avoided.**
  - **Can't use the higher pole traps where the lowest micro-motion is achieved.**

•Solution:

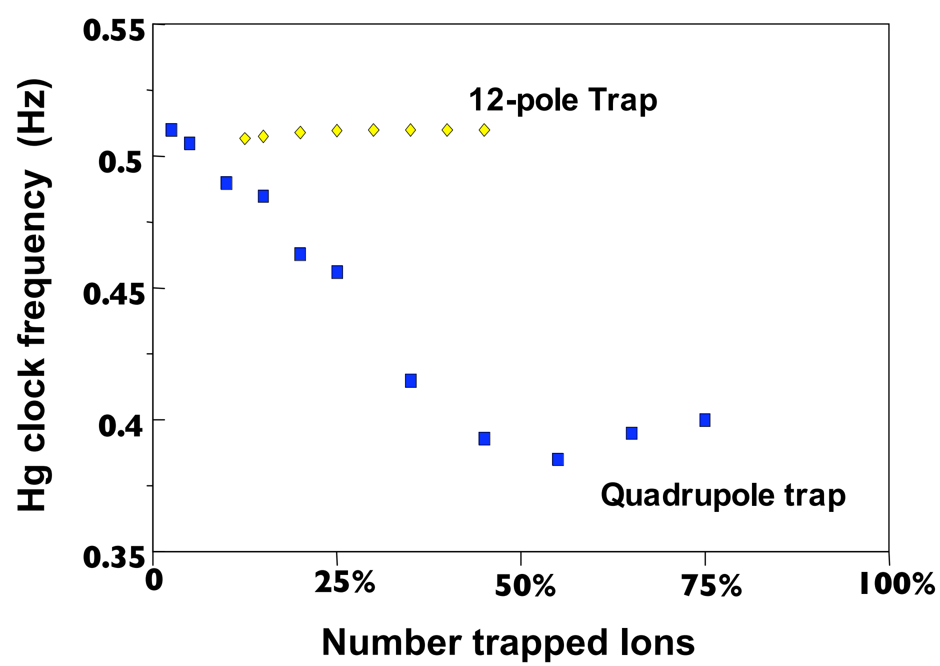
Operate the Higher pole trap at different frequency (e.g., ~2x higher). Holes open and close faster than ions can drift through.

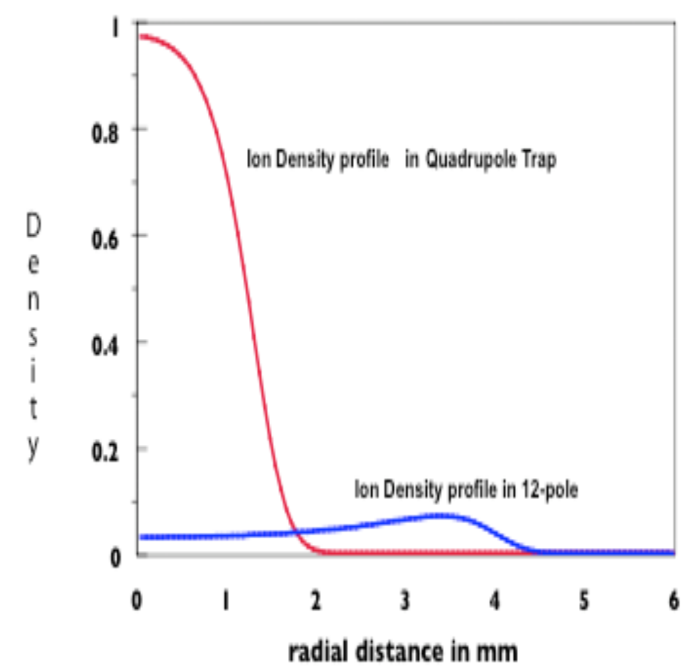
Well depth ~ $\frac{\Omega^2}{k^2}$ **can be preserved as k gets large.**

Ion-number sensitivity is drastically reduced

Ion-number frequency pulling is at least 20x reduced from LITS quadrupole !

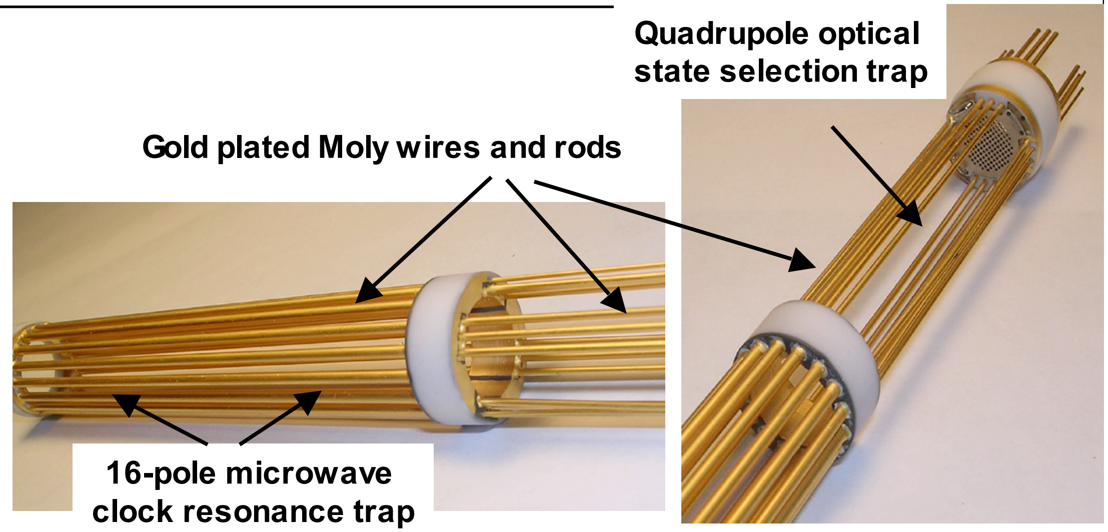
It doesn't behave like ion heating and 2nd-order Doppler frequency pulling !

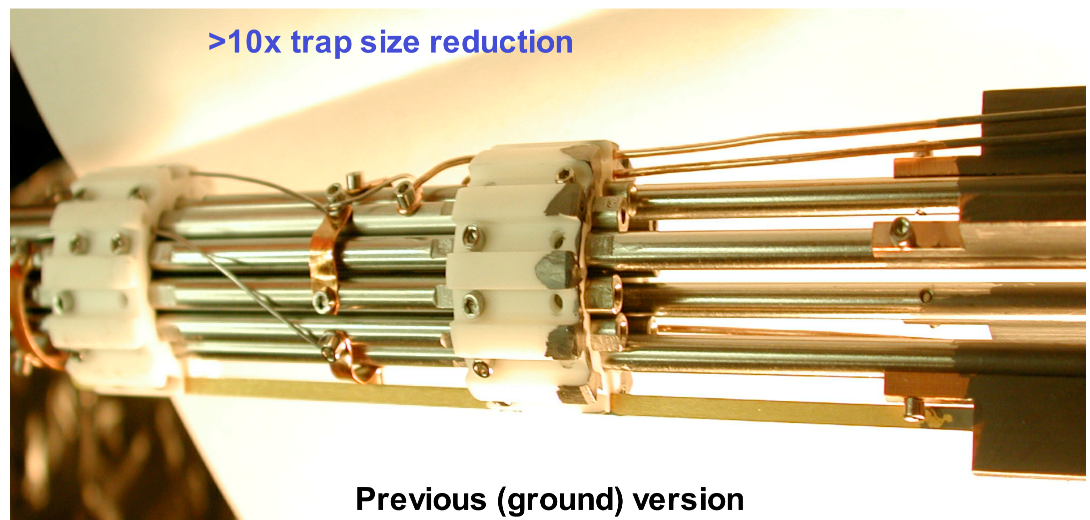




Miniaturizing Ion Traps

- State selection/optical interrogation in quadrupole; microwave clock resonance in higher multipole trap.
- Ion traps are brazed, “one piece” with metallized electrical inter-connects; no screws, etc. used as fasteners.
- Non-magnetic parts required for high Q atomic resonance ($Q \sim 3 \times 10^{11}$).
- 16-pole provides better isolation to stray external fields, for 0.056” moly rod size.
- 4-pole load trap has twice the well depth of the previous version; better ion load rates, higher SNR in clock resonance.



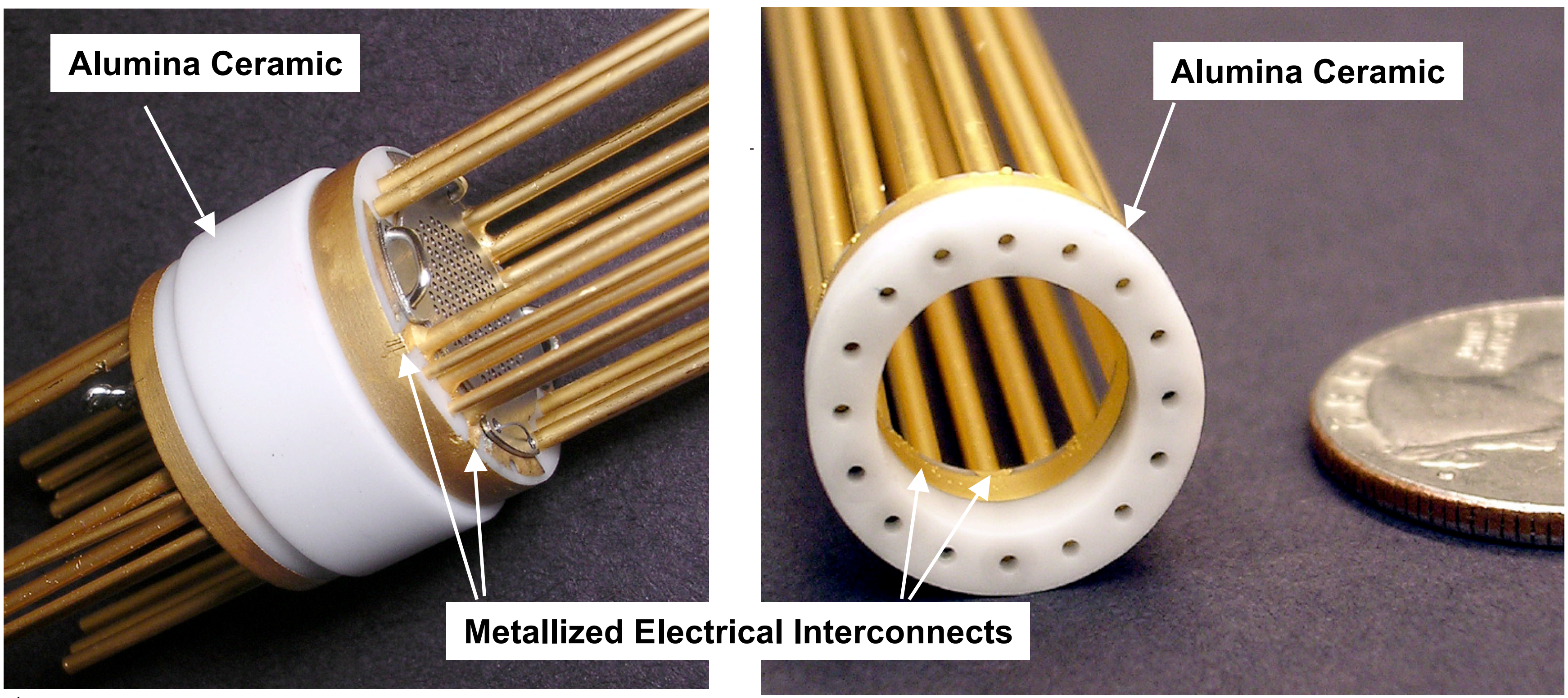


Previous (ground) version
>100 titanium 0-80 screws

John Prestage

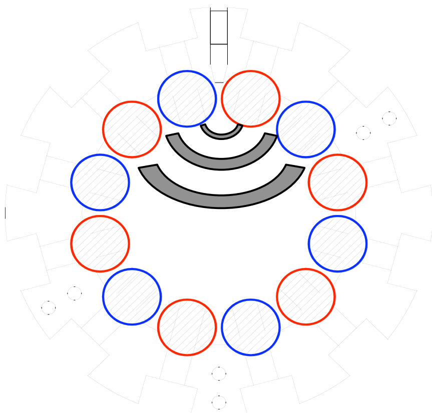
Full Trap Design, Fabrication Completed

- 4 trap assemblies procured and delivered, 5th to be inspected for electrical connection integrity;
  - **First 2 assemblies were "learning curve" fabrications, mechanical/magnetic/electrical problems**
  - **Remaining 3 are ready for clock tests.**



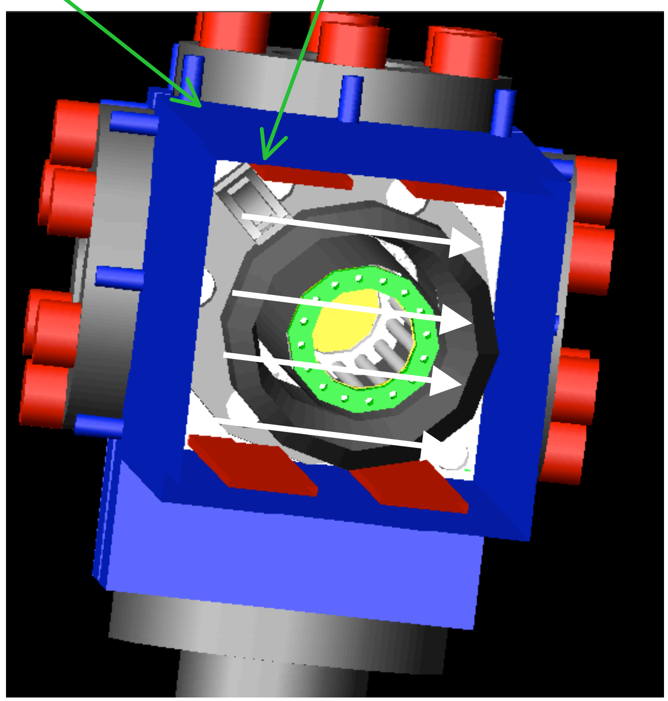
Physics Package Assembly

Inner Shields, field coils, and WR-19 waveguide

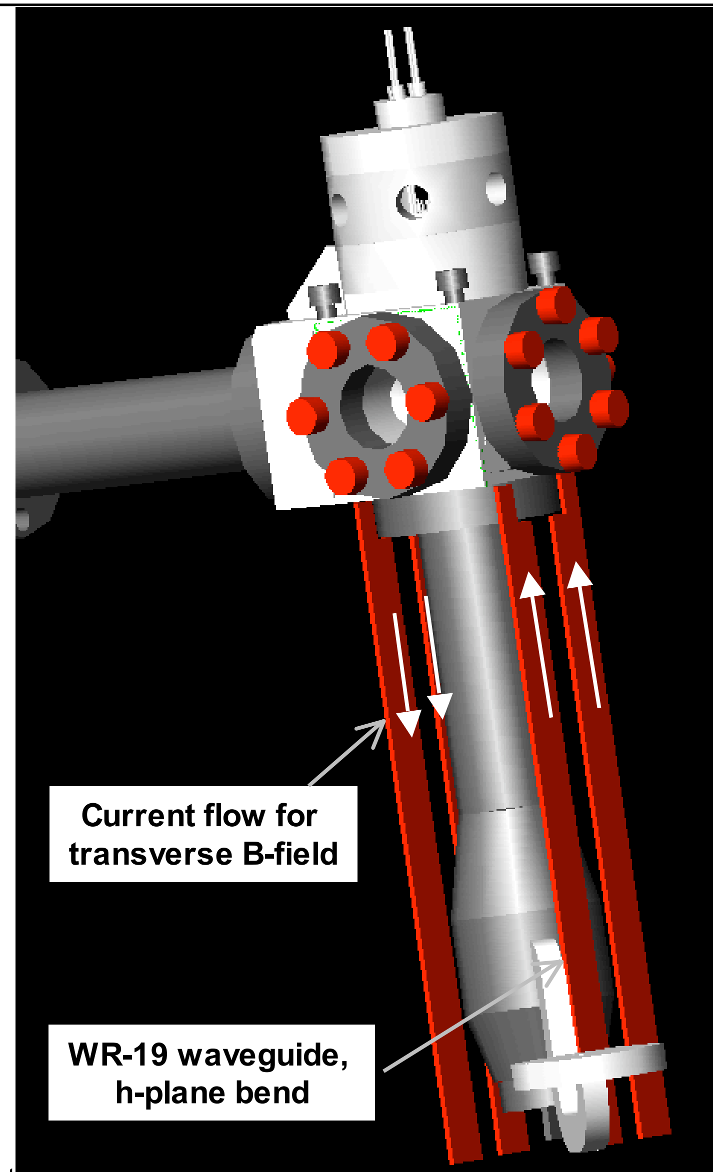


Inner magnetic shield square cross-section

Microwaves propagated trap axis avoids carrier suppression of 40.5 GHz



Doppler-free clock transition requires transverse k vector

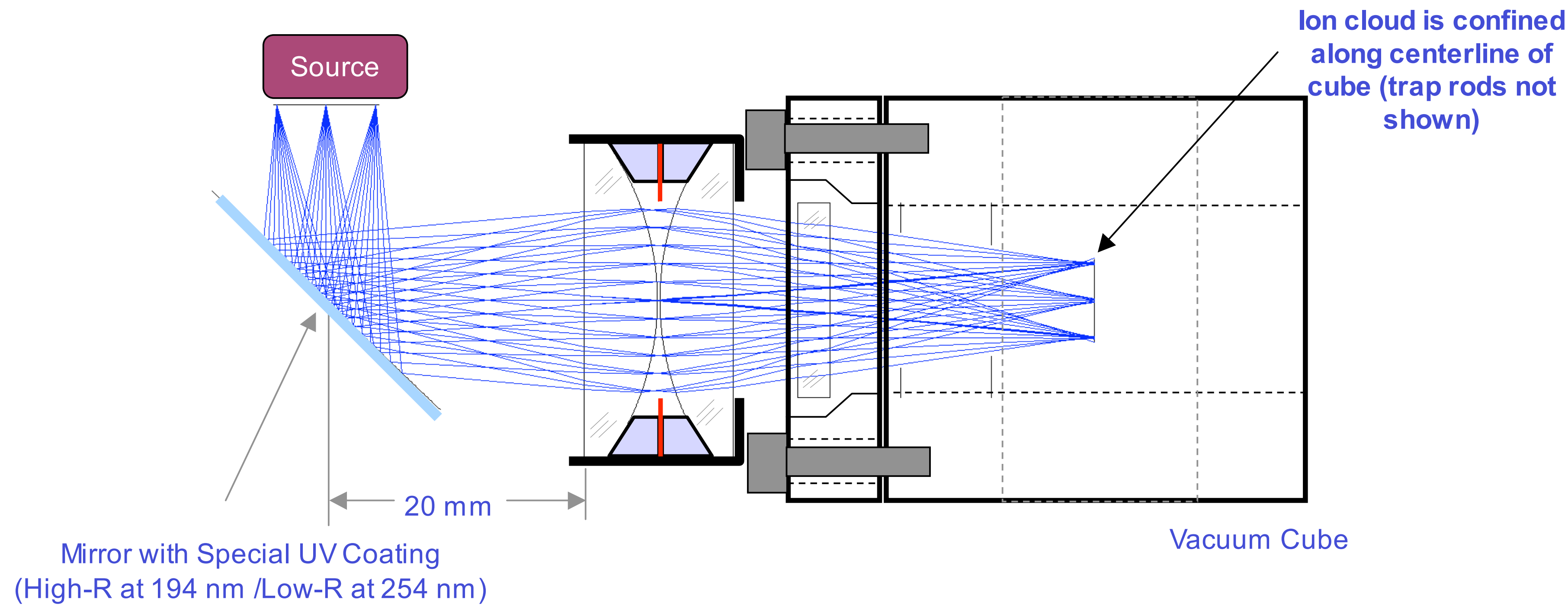


Current flow for transverse B-field

WR-19 waveguide, h-plane bend

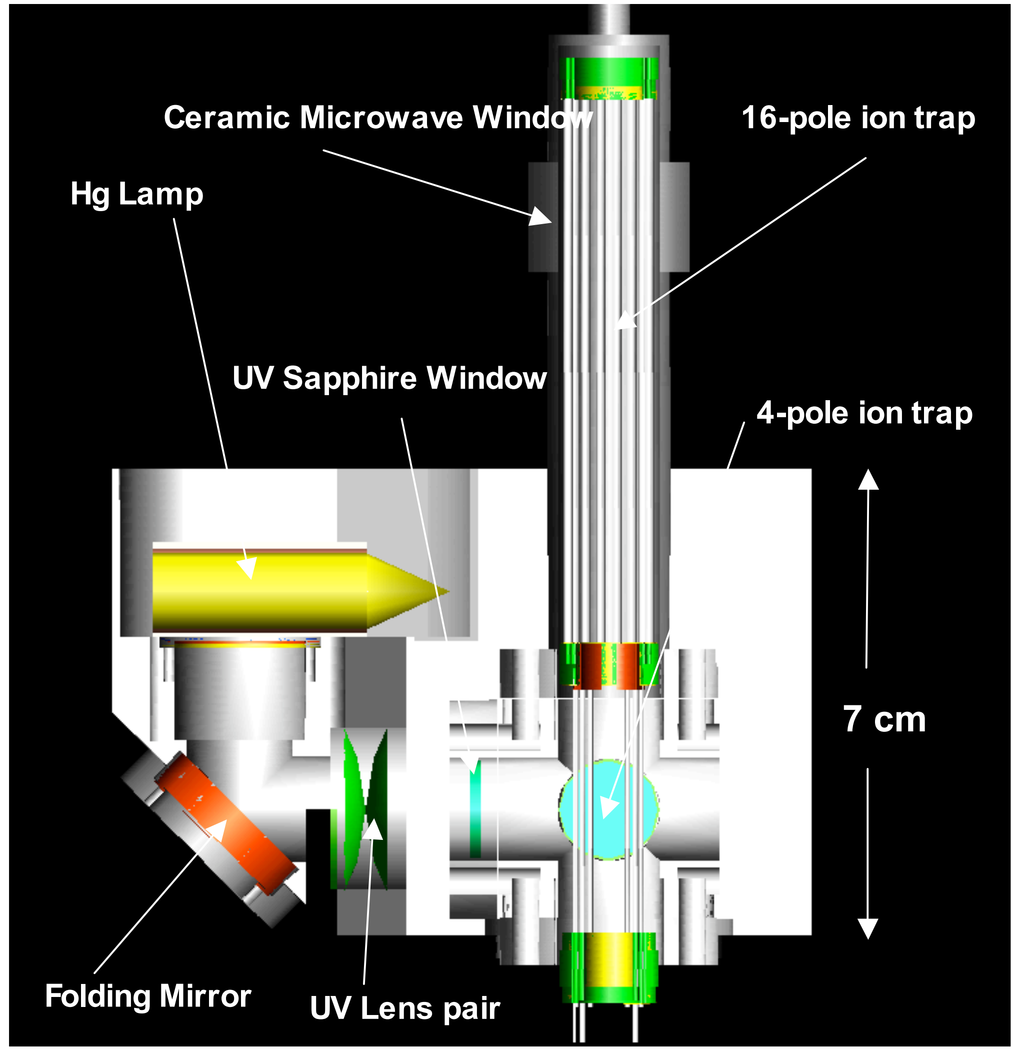
Optical System - 2 lenses and 1 mirror

- **Design Uses 3 identical optical arms, each with 2 lenses, an UV dichroic folding mirror, and a UV-grade sapphire vacuum window.**
  - **Ion fluorescence detection arms are oriented perpendicular to input light arm.**
- **Optics features:**
  - **UV-grade silica, 10-5 scratch-dig polish, antireflectance coated to <0.5% per surface.**
  - **Surface roughness is a source of stray light in the UV; laser optical polish used.**
- **Clock optical components are also used in semi-conductor photolithography (ArF 193 nm laser)**



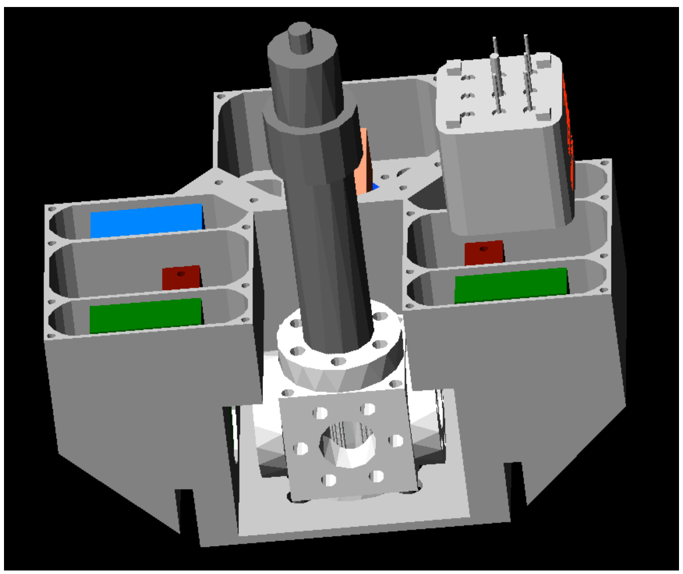
Modular Compact Optical System

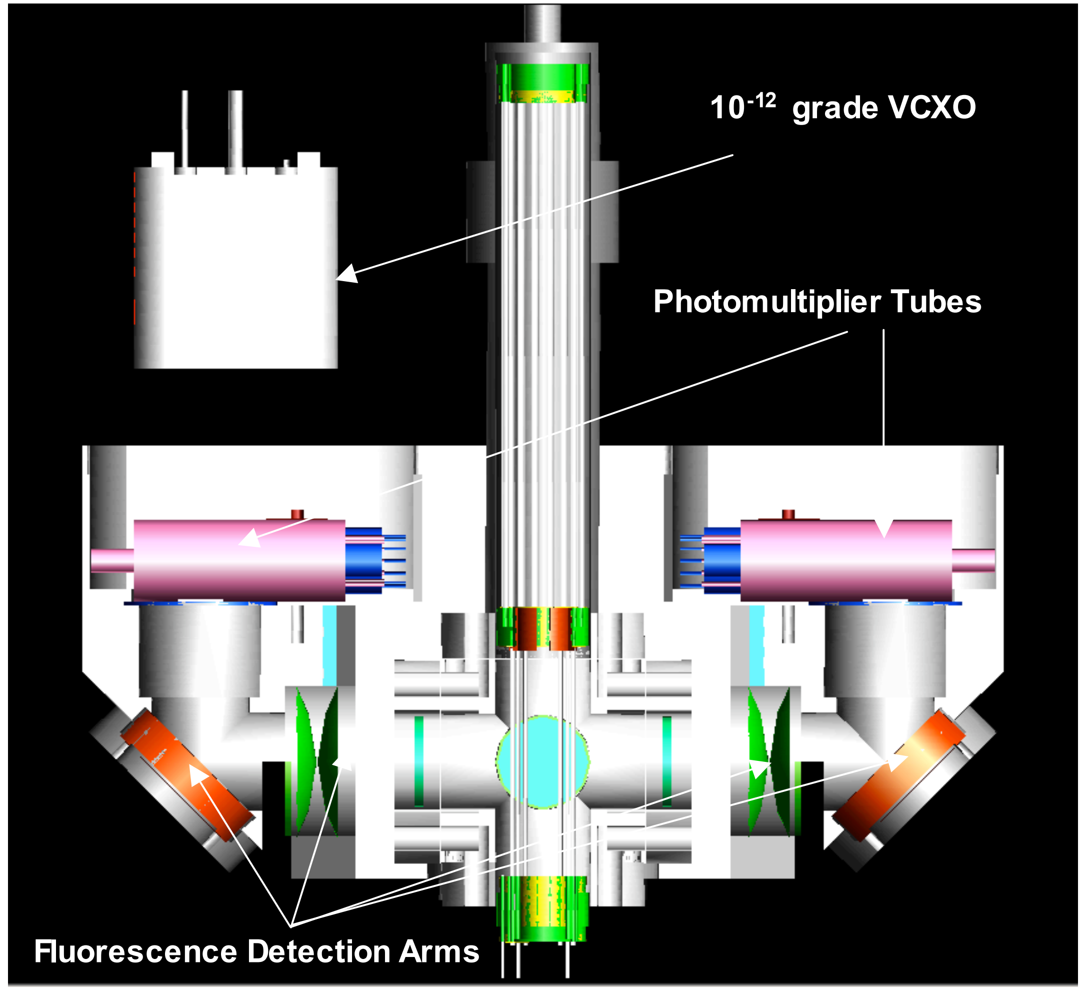
- Optical Mount is single piece modular
  - can be tested for internal alignment without the ion trap
- Lamp resonator and exciter power electronics are integrated into module
- Sensitive detector electronics are isolated from lamp exciter power via RF-tight gasket compartments



Modular Compact Optical System

- UV light detectors with power supply, amp/discriminator chip are integrated into module.
- Isolated from RF power in lamp driver module with RF-tight compartments as shown below





Compact Optical System Package

Packaged Optical Electronics - UV source and fluorescence detectors

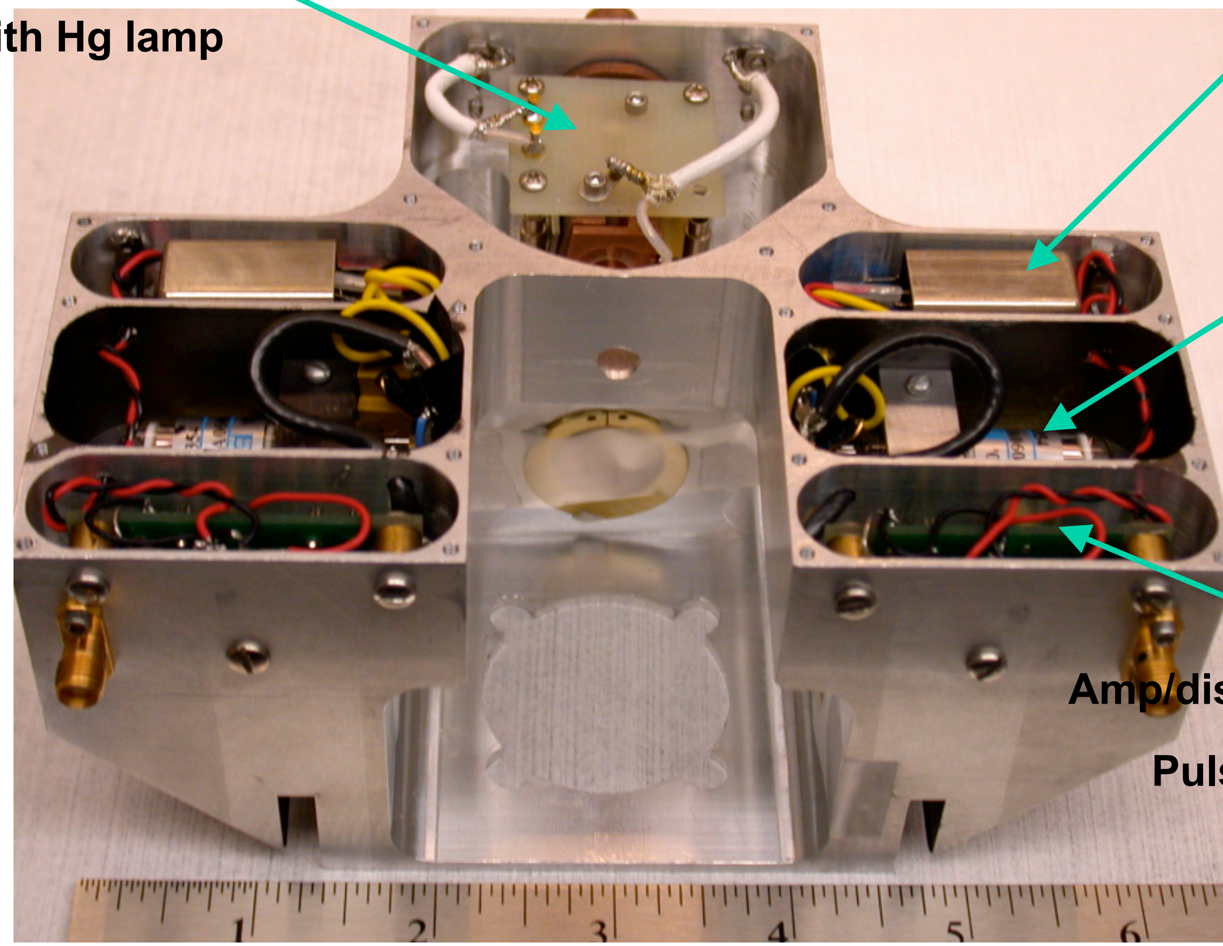
Lamp Resonator with Hg lamp

High-Voltage supply for PMT

Photo-multiplier Tube (PMT) with base

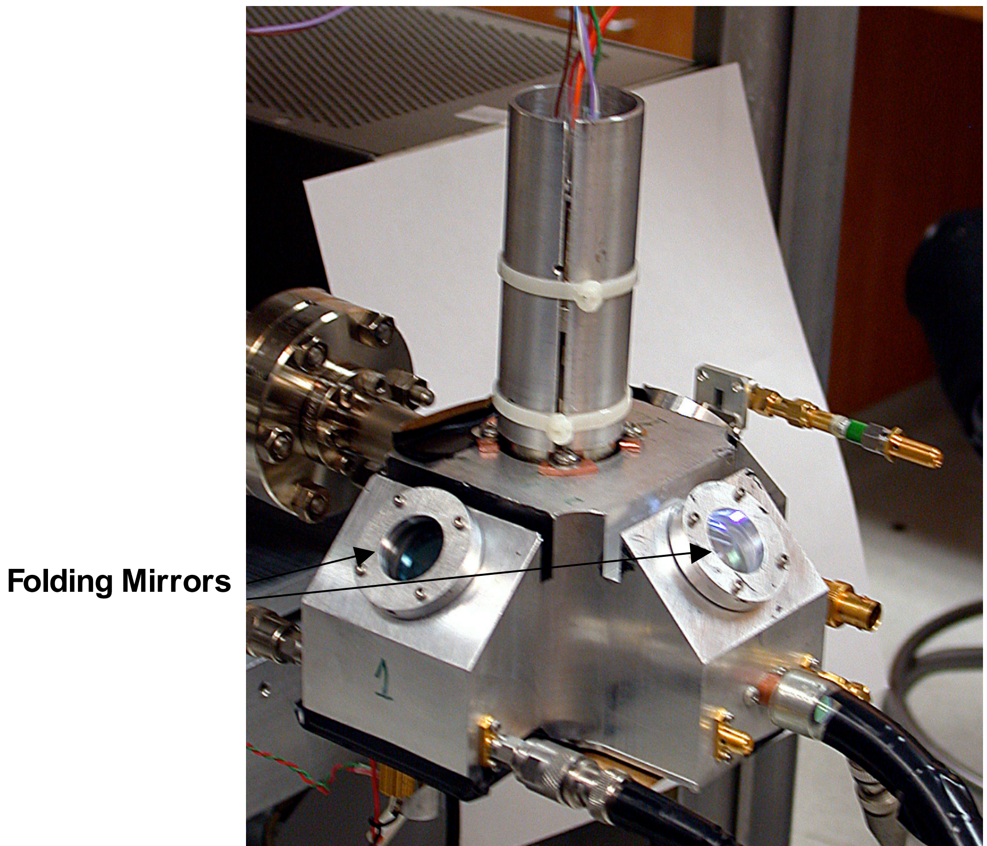
Amp/discriminator PC board

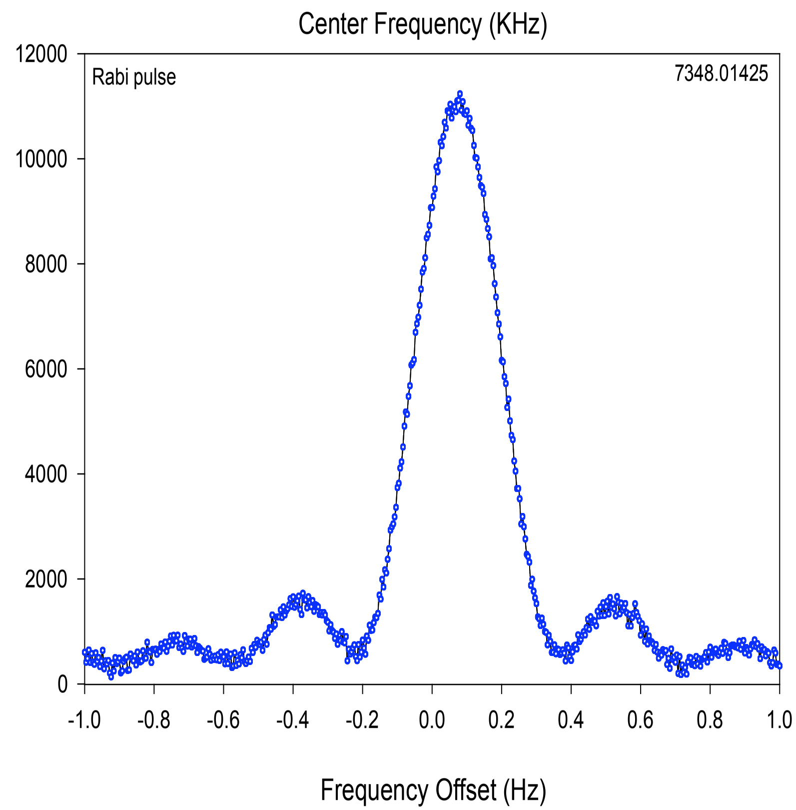
Pulse out to counter



Liter Hg Ion Clock, $10^{-13}\tau^{-1/2}$

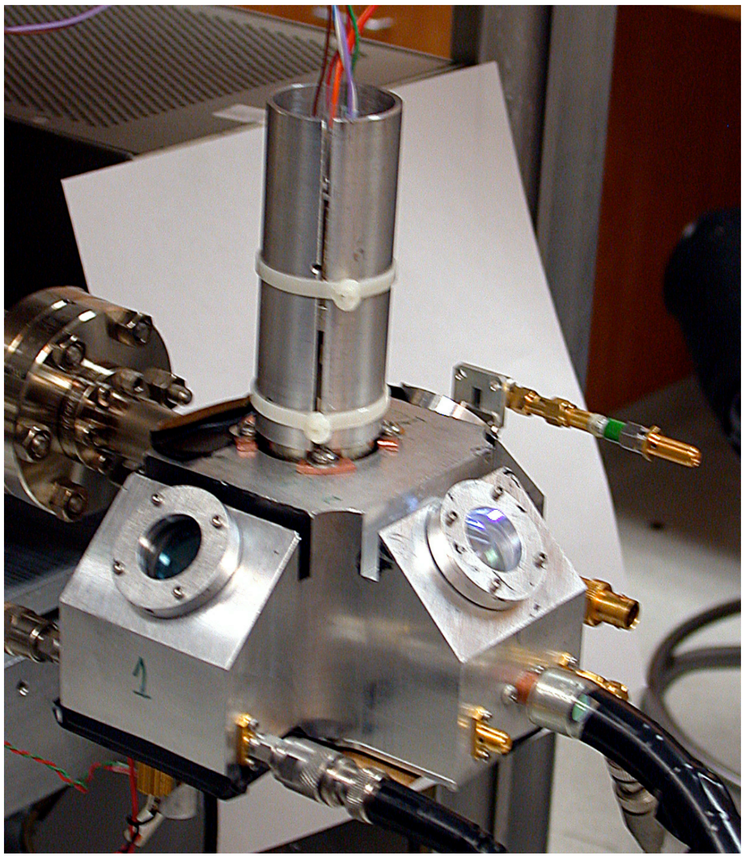
- Demonstrated short-term stability $10^{-13}\tau^{-1/2}$, as good as the 100x larger ground-based package.
- Line Q ~ 2 x 10^{11} in the first measurement (shown at right)
- No magnetic shields yet installed

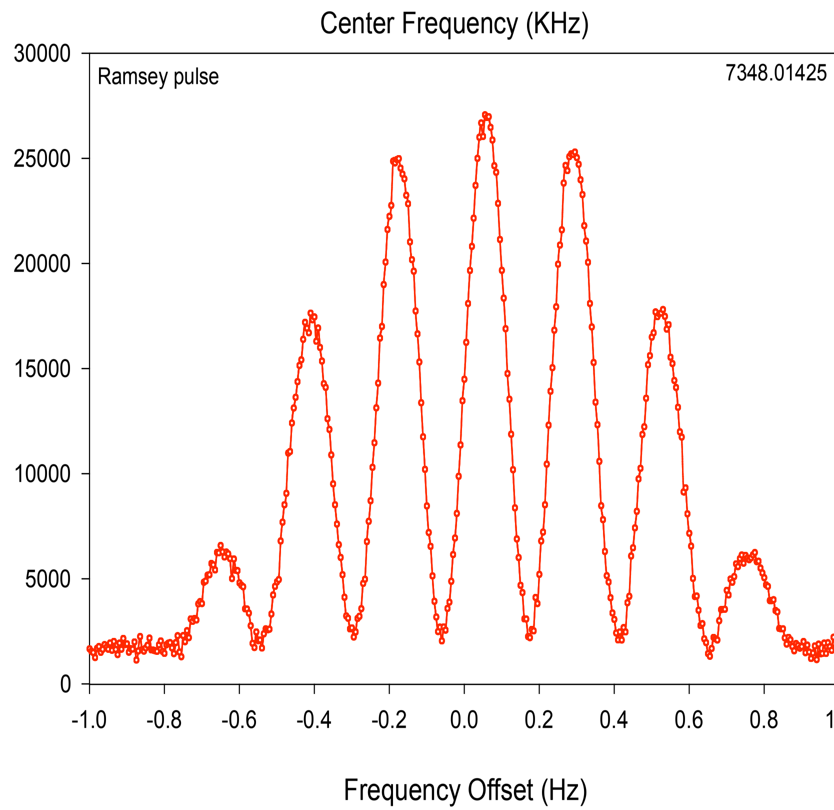




Liter Hg Ion Clock, $10^{-13}\,\tau^{-1/2}$

- $Q \sim 4 \times 10^{11}$ in measurements shown at right.
- No magnetic shields for these measurements.
- $Q \sim 10^{12}$ in later measurements.





Ion Clock Redesign - Getter Pumping

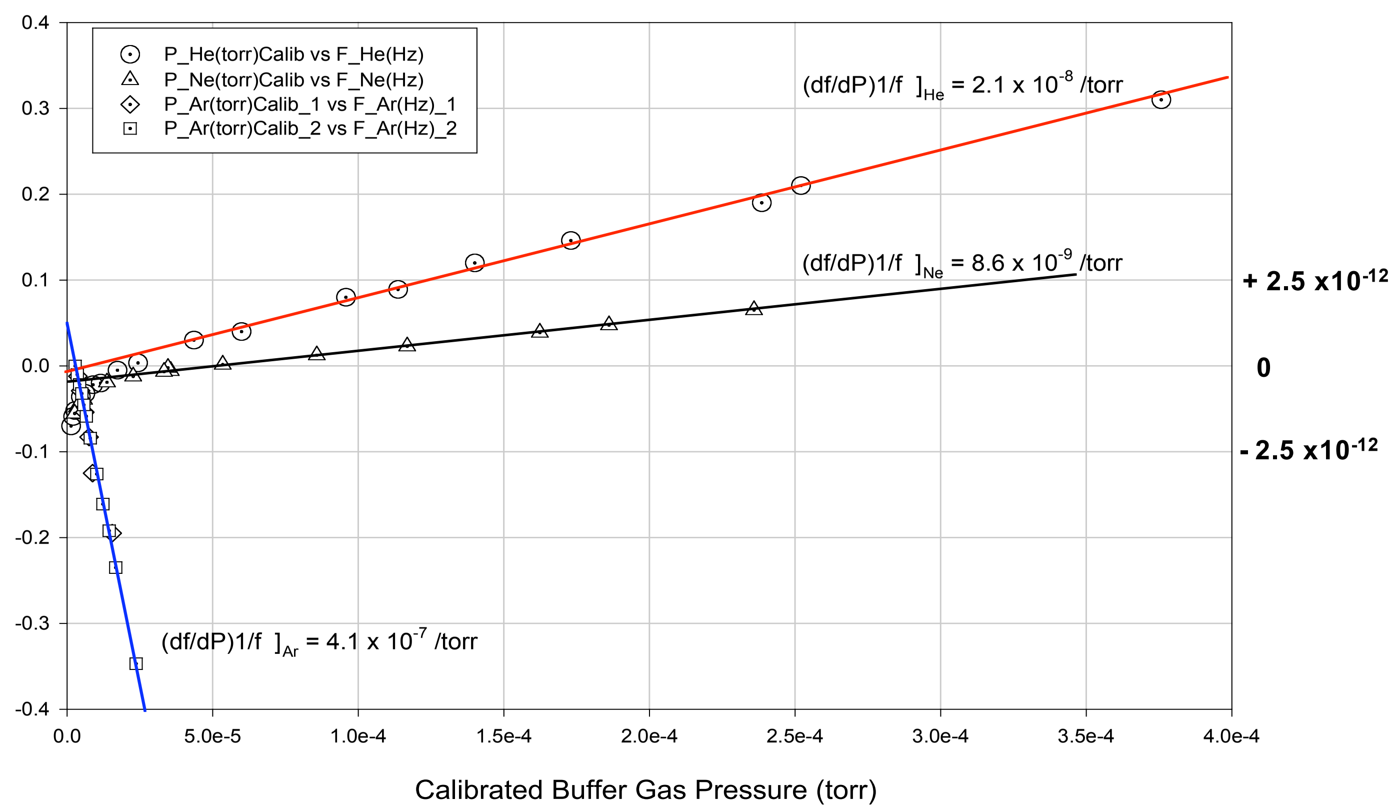
- **Replace mechanical pumping and buffer-gas flow system.**
  - Light, noble buffer gas required to cool ions to room temperature, increase number of captured/trapped ions.
  - UHV prepared, filled with buffer gas and getters, then sealed.

- **Getter pumping, bulk and surface getters (Benvenuti, et al, 1998)**
  - Consumes no mass, power, little volume.
  - Will not pump or otherwise consume buffer gas.

- **Requires UHV design and fabrication.**
  - 400 C Sapphire windows developed.
  - Low gas load field emitter filament employed.
  - Titanium vacuum jacket materials.
  - 400 C bake-out with sealed getters, filled to ~ 10^{-5} Torr with Ne buffer.

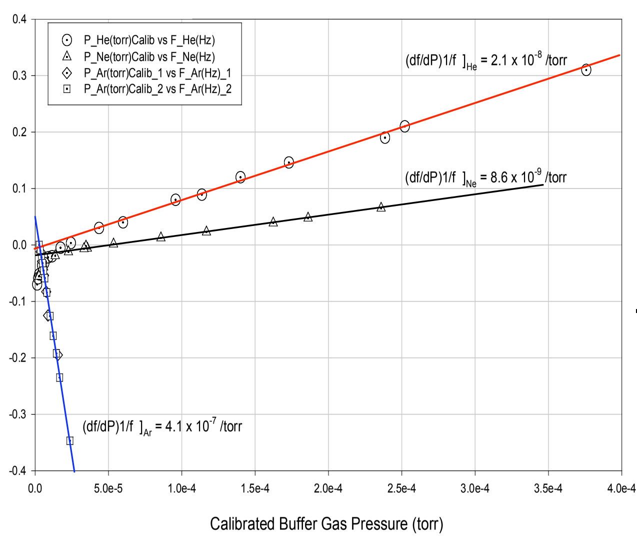
Ion clock uses buffer gas to "cool" ions

- Hg^+ clock uses ~ 10^{-5} Torr "buffer" gas to cool ions to near room temperature; helium is traditionally used.
- Investigated neon and argon as substitutes; Found 3 times less clock frequency changes in neon than helium; 20x more in argon
- Additionally, neon pressure varies 5x less than helium for a 1 C temperature change
- Frequency pulling < 10^{-15} per degree C temperature change !



Summary

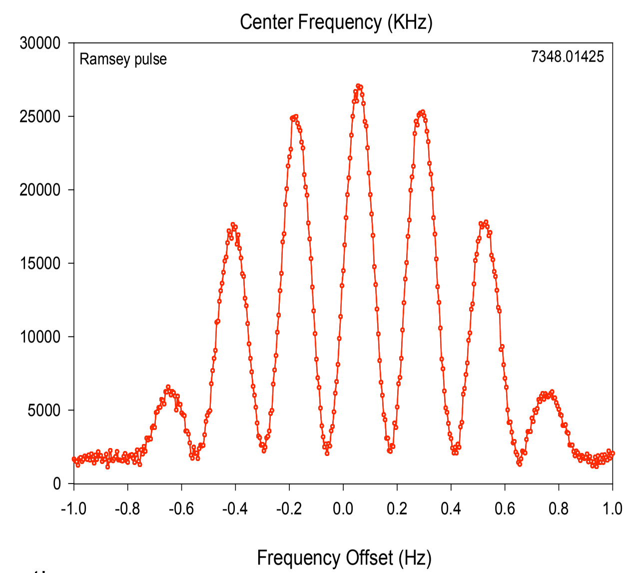
- Microgravity friendly, 1-g gravity friendly.
- 10^{-15} stability in a 1-2 liter package seems feasible.
- Demonstrated $10^{-13}\,\tau^{-1/2}$ in ~ 1-liter physics package breadboard.
- Demonstrated 3x reduction in buffer gas shift by neon.
  - Frequency pulling < 10^{-15} per degree C temperature change via buffer gas variations



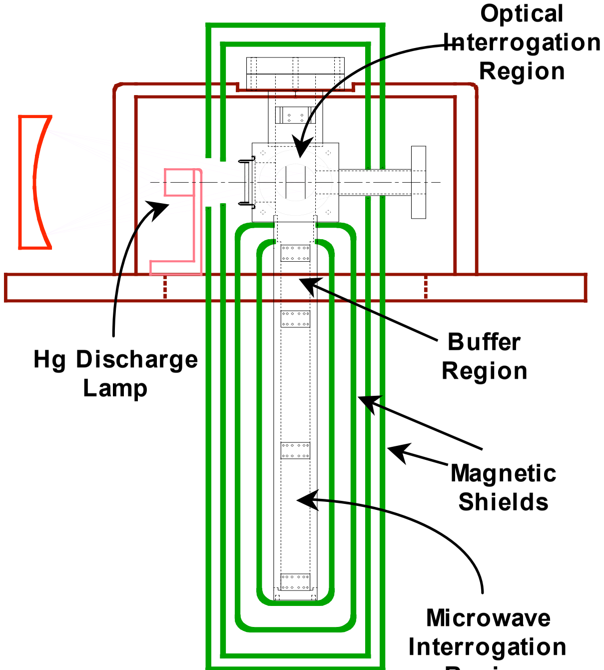
+ 2.5 x10^{-12}

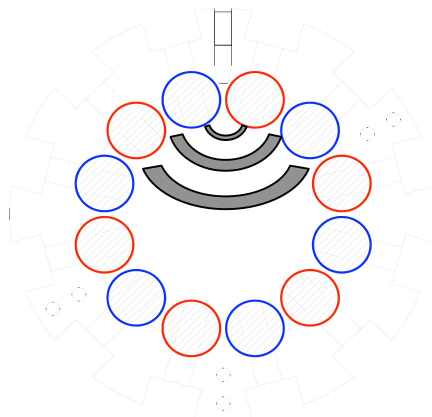
0

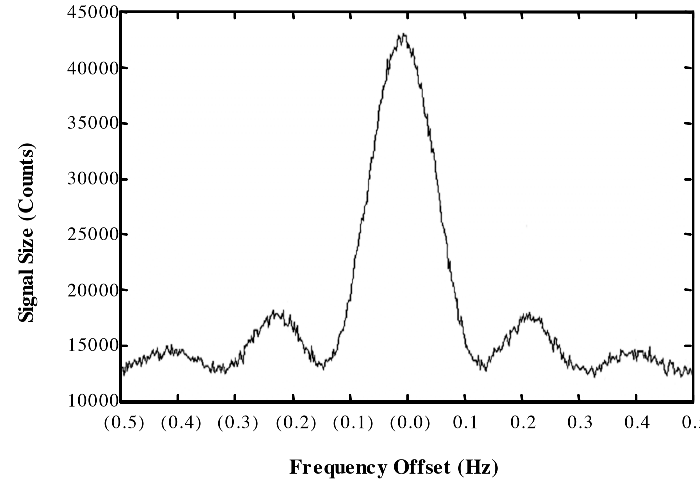
- 2.5 x10^{-12}



Doppler-free and doppler-broadened resonance in 12-pole trap





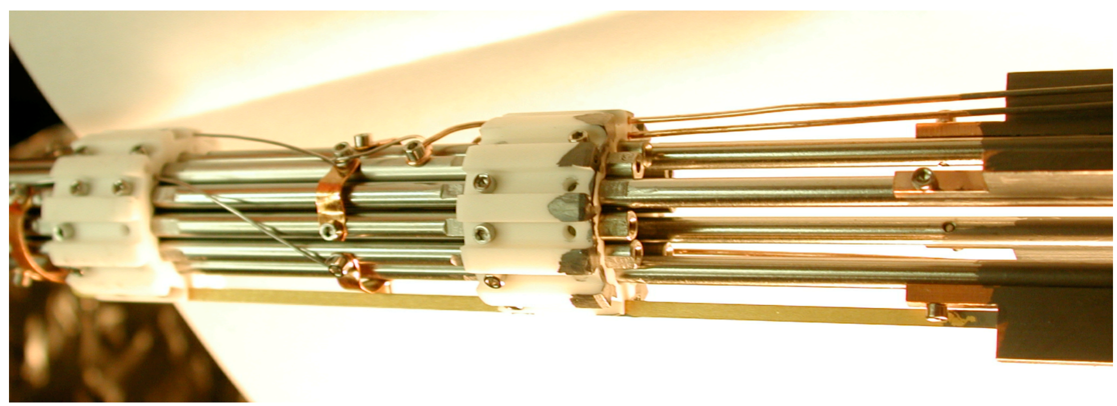


Doppler-free clock transition for transverse k vector propagation (~ 100 mHz)

Propagation along the trap axis determines Ion temperature; 1% width measure gives $2x10^{-15}$ 2nd Doppler determination

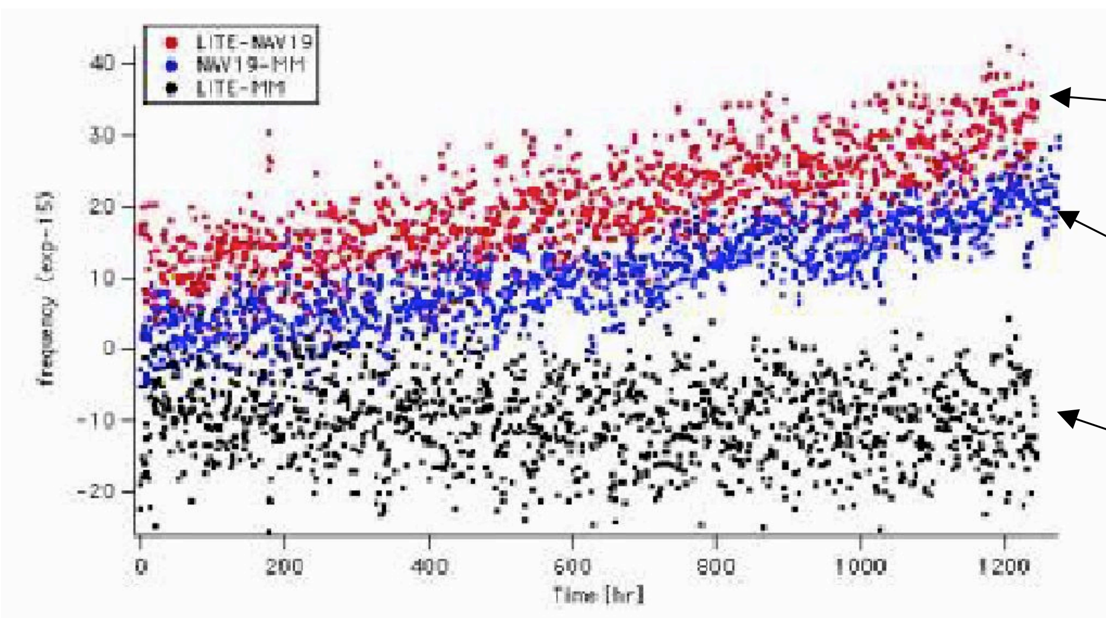
$$\delta\nu_{Doppler} = 2\frac{\upsilon_0}{c}\sqrt{\frac{2k_B T \ln 2}{m}}$$

$$= 35.6\sqrt{\frac{T(K)}{300}}[kHz]$$



Ion clock redesign for space

- Small Ion Clock Approach and Heritage
  - No lasers, uwave cavities, cryogenics, atomic beams, etc.
  - Ions are electrically shuttled between separate optical and microwave traps.
    - Each trap is optimized for its task: quadrupole for optical state selection; multi-pole for microwave clock.
  - Very good stability shown in USNO Timescale running “open loop”
- “Open loop” operation means no self-measurements of frequency offsets: Zeeman, ion temperature,… etc.
  - Fewer parts and procedures, produces stable output continuously
- Ion clock is not so sensitive to temperature fluctuations
  - Measured *unshielded* temperature coefficient of few 10^{-15} per C.
  - No bulky temperature isolation needed.



Ion clock vs Nav-19 H-Maser

Nav-19 (H-Maser) vs mean of 10 H-masers

Ion clock vs mean of 10 H-Masers
Showing < $5x10^{-17}$ per day
Frequency drift between JPL ion clock and USNO time scale