Primary Frequency Standards at NIST

S.R. Jefferts
NIST – Time and Frequency Division

Outline

- Atomic Clocks - general
- Primary Frequency Standard
  - Beam Standards
  - Laser-Cooled Primary Standards
- Systematic Frequency Shifts in Primary Frequency Standards
- Near Future –(maybe) space clock
- More Distant Future – optical clocks & redefinition

Acknowledgements

Tom Heavner, Liz Donley and Tom Parker - the rest of the NIST-F1 team

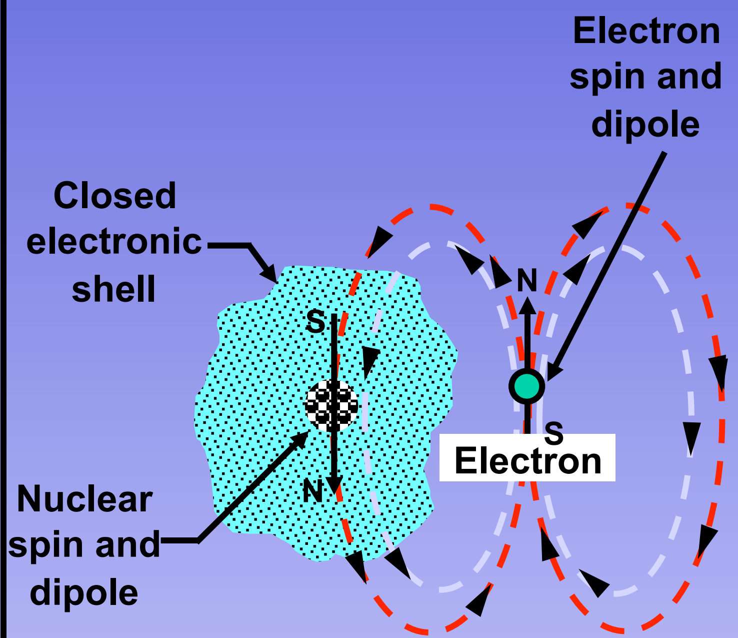
Filippo Levi – IEN Turin Italy – who has worked with us on fountains for years

Jon Shirley – for answering all the theory questions

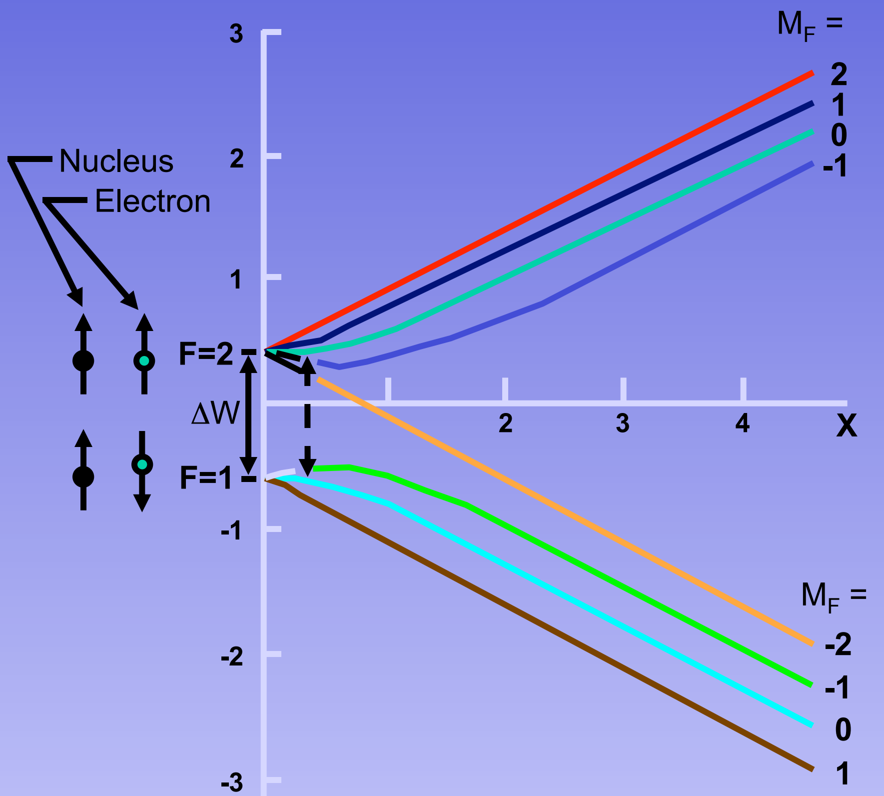
Len Cutler, Mike Garvey and Bill Riley – the real experts in the field who always have patient, well thought out answers to (sometimes stupid) questions and also provide last minute view graphs for talks!

Atomic Clocks - General

An Energy View of an Atom



Hydrogen-like (or alkali) atoms



Hyperfine structure of ^{87}Rb, with nuclear spin I=3/2, $\nu_0=\Delta W/h$=6,834,682,605 Hz and $X=[(-\mu J/J)+(\mu I/I)]H_0/\Delta W$ calibrated in units of 2.44 x 10^3 Oe.

A Little Quantum Mechanics

- The allowed states (configurations) of an atom have discrete (quantized) energies, in the long run, atoms are only allowed to exist in these quantized states (these are the only stable states)
- Atoms of the same element (and isotope) are indistinguishable, for example, all cesium 133 atoms are the same
- Energy and Frequency are equivalent, E=hν where h is Plank's constant
- Atoms move between their allowed energy levels by absorbing or emiting a photon of the correct frequency for the difference between the beginning and ending energies.

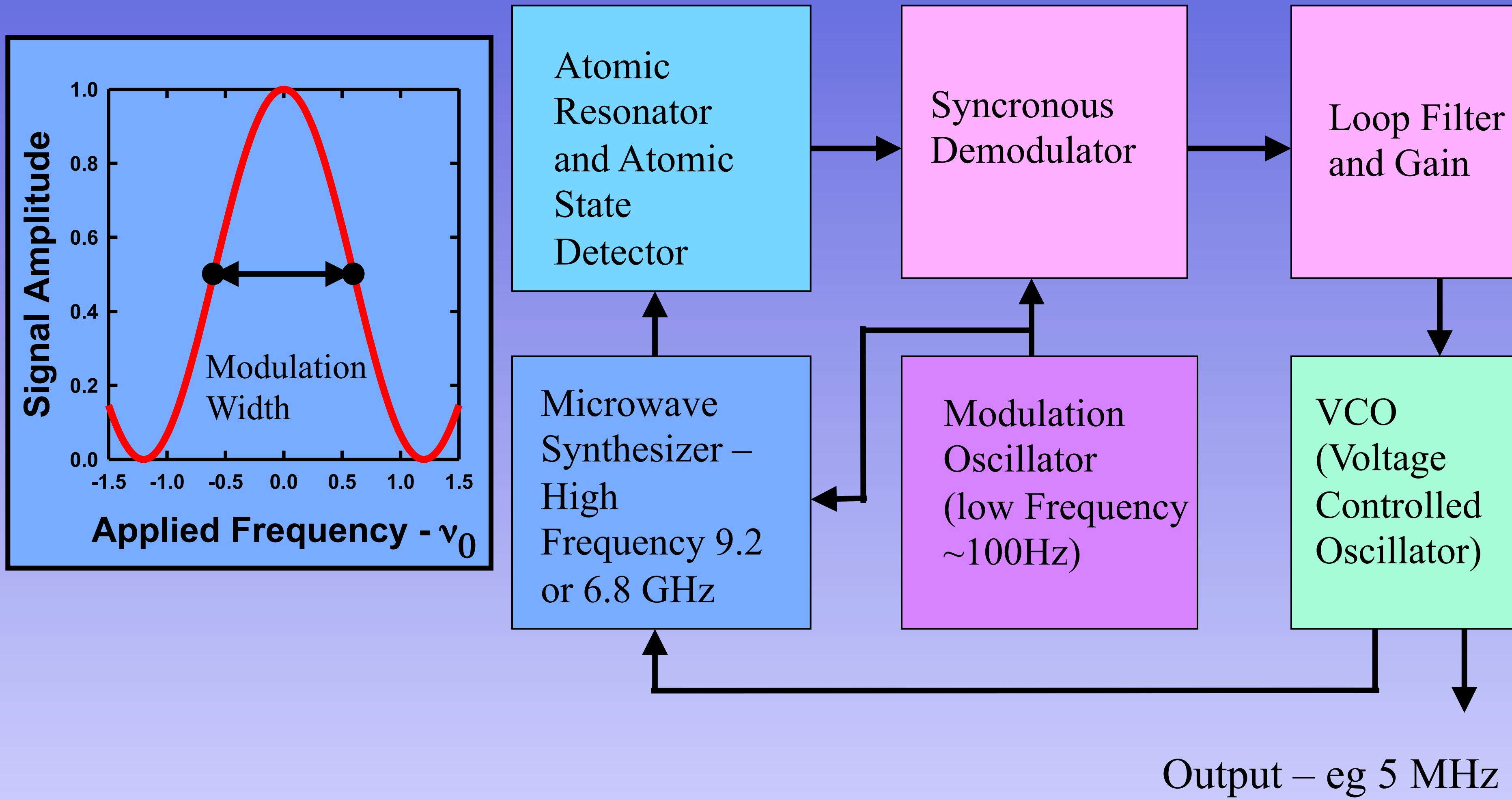
$$\upsilon = \frac{E_{final} - E_{initial}}{h}$$

- The “rules” just given explain the high long term stability of atomic frequency standards. The atoms behave (define the frequency) the same way tomorrow that they do today and did yesterday. In an ideal atomic standard this would be rigorously true, in the real world the atoms interact with their environment and experience slight frequency shifts.
- These shifts are typically caused by things like
  - Less than perfect magnetic shielding
  - Collisions between atoms
  - Gravitational effects
  - Thermal radiation
  - Electronics drifts
  - etc

Microwave Field

- The change in state (up to down) is driven by an microwave field
- The interaction is between the electron and the field…essentially the electron is “flipped”
- The “clock” transition is, to first order, not shifted by a magnetic field, but requires that the magnetic field of the microwaves be parallel to the C-field (quantization axis)

Block Diagram – simplified a little



Clock Performance

Clock Stability is given by:

$$\sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

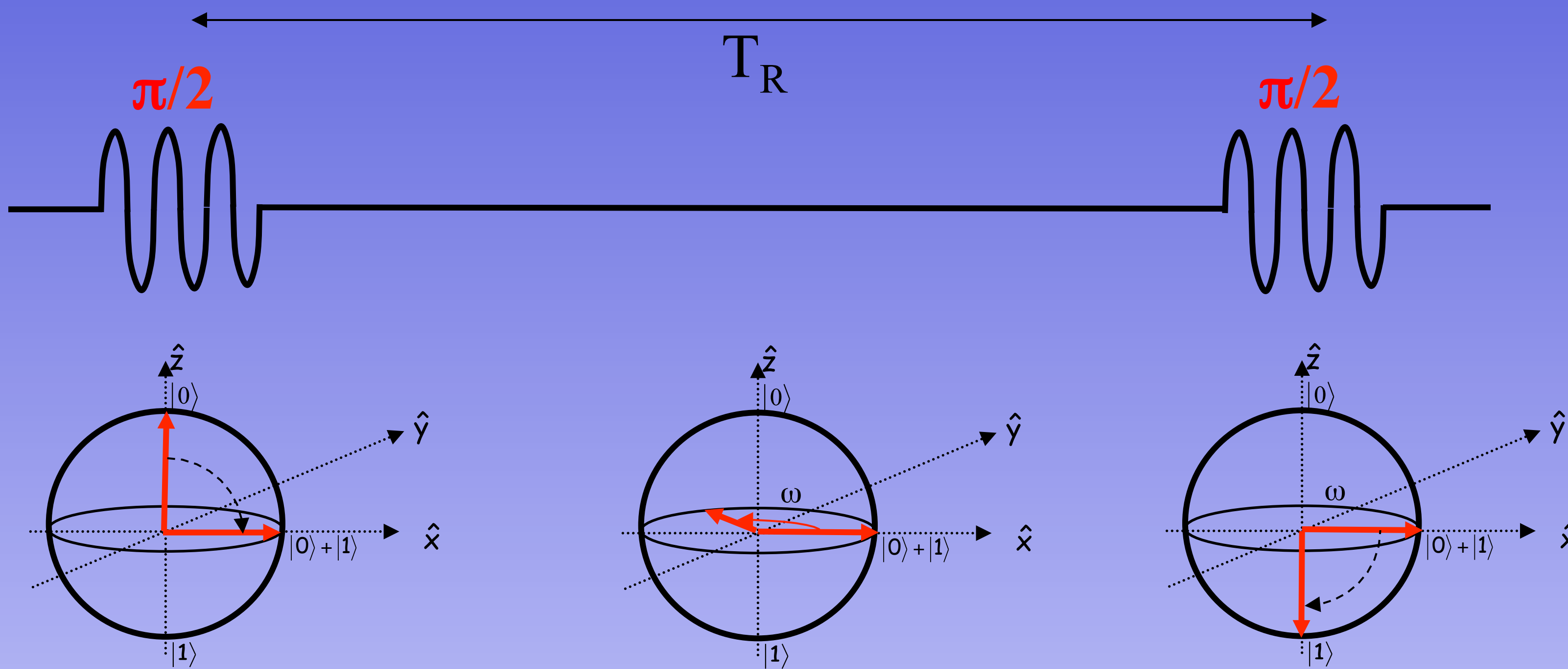
Atomic Line Q

Signal to Noise

Clock Stability can be improved by:

- Increase Ramsey (Observation) Times (Decrease $\Delta\omega=1/T_{Ramsey}$)
- Increase The Frequency of the Clock Transition
- Improve the S/N

Ramsey's method of separated oscillating fields



The final projection depends on the relative phase between the superposition and the microwave field!

Laboratory Primary Frequency Standards

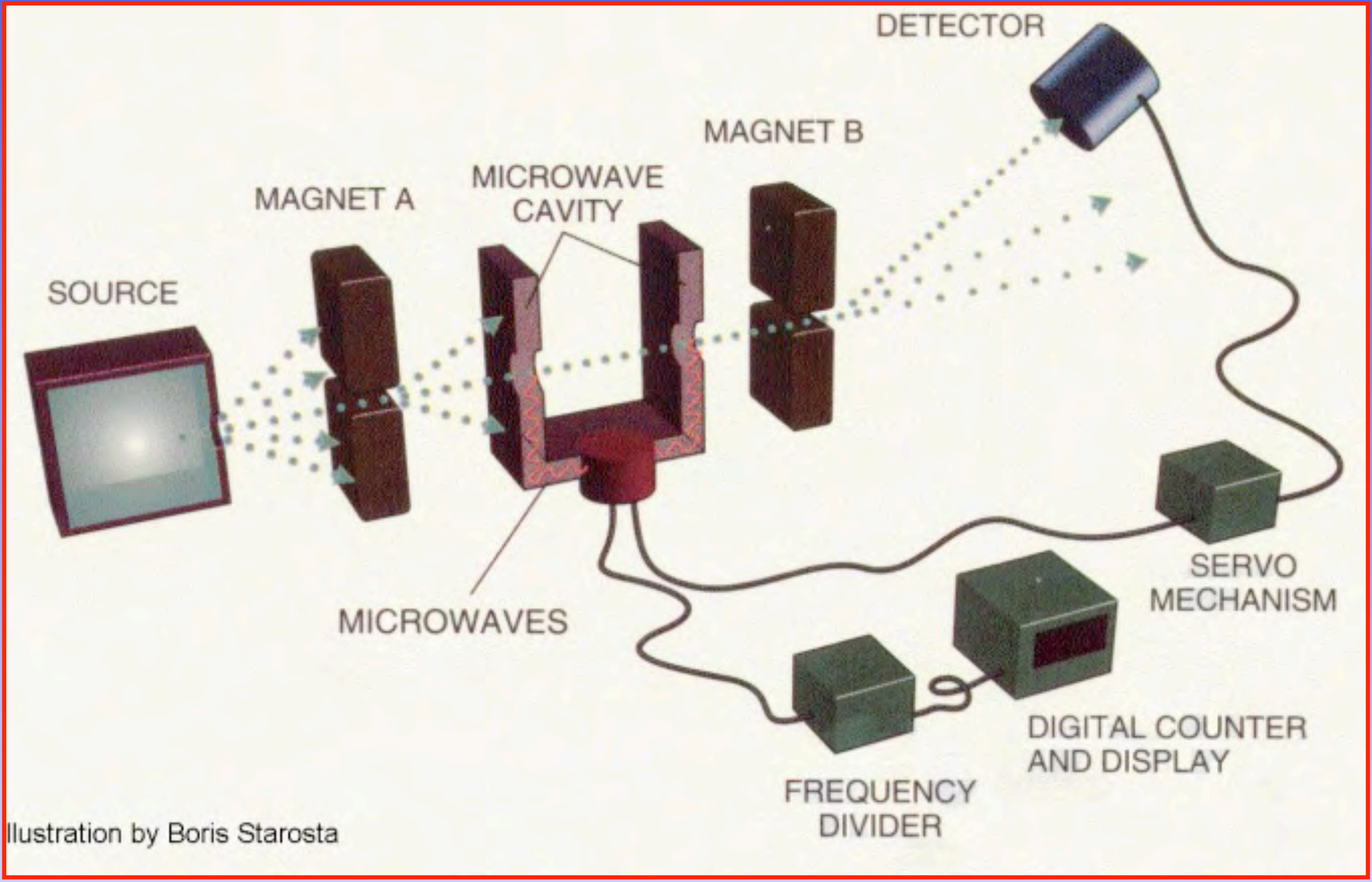
Definition of the Second

- The second is defined as 9,192,631,770 cycles of the hyperfine transition of a cesium-133 atom which is isolated from its environment (eg T=0, B=0, etc) and at rest on the geoid of the earth (about “sea-level)
- Note that what is really being defined is the frequency of the transition as being 9.192631770 GHz.

Accuracy and the Environment

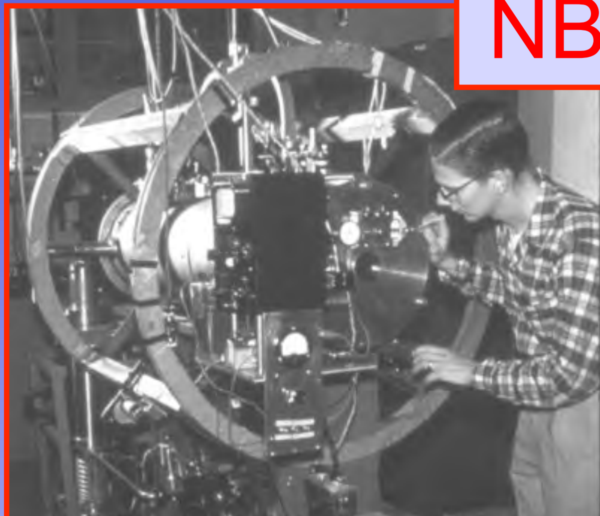
- The definition of the second is essentially impossible to realize, we cannot get to absolute zero, the magnetic field is never zero etc.
- Laboratory (Primary) Standards deal with this by measuring the effect of these environmental frequency shifts and correcting the output frequency of the clock to achieve a, more or less, close approximation of the definition.

Magnetically Selected Thermal Beam



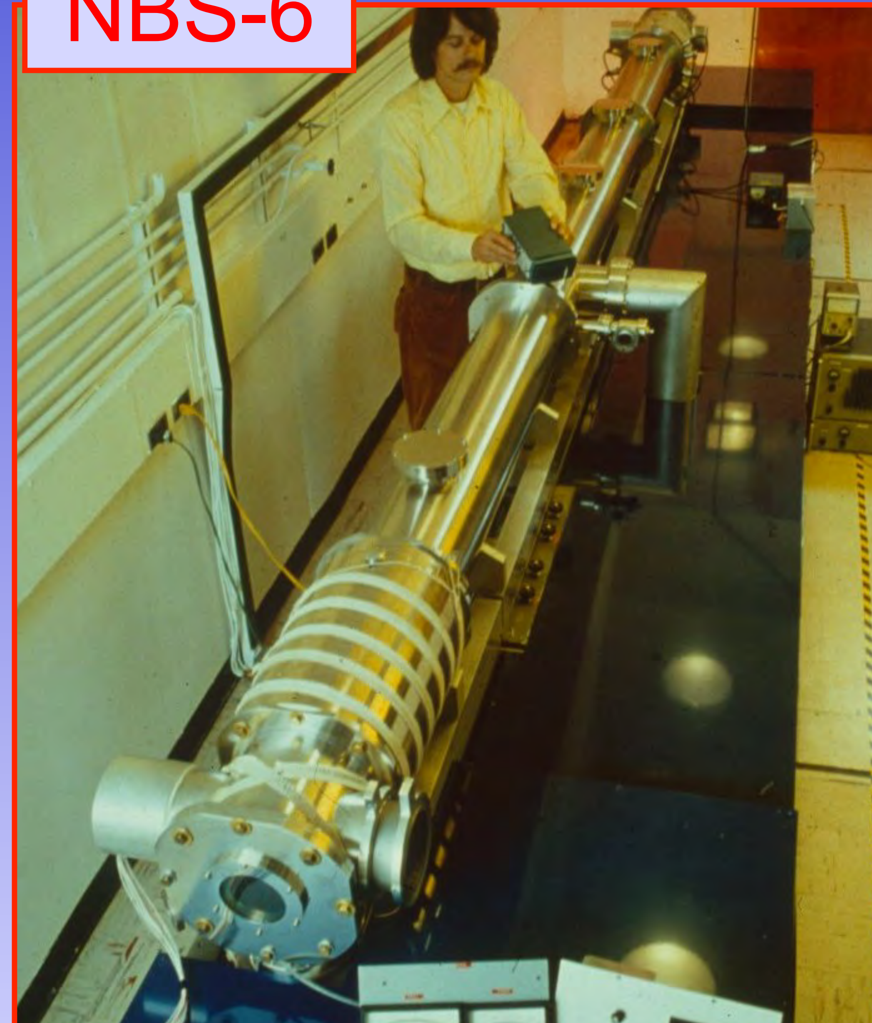
Thermal Cesium Beam Clocks at NIST

NBS-1

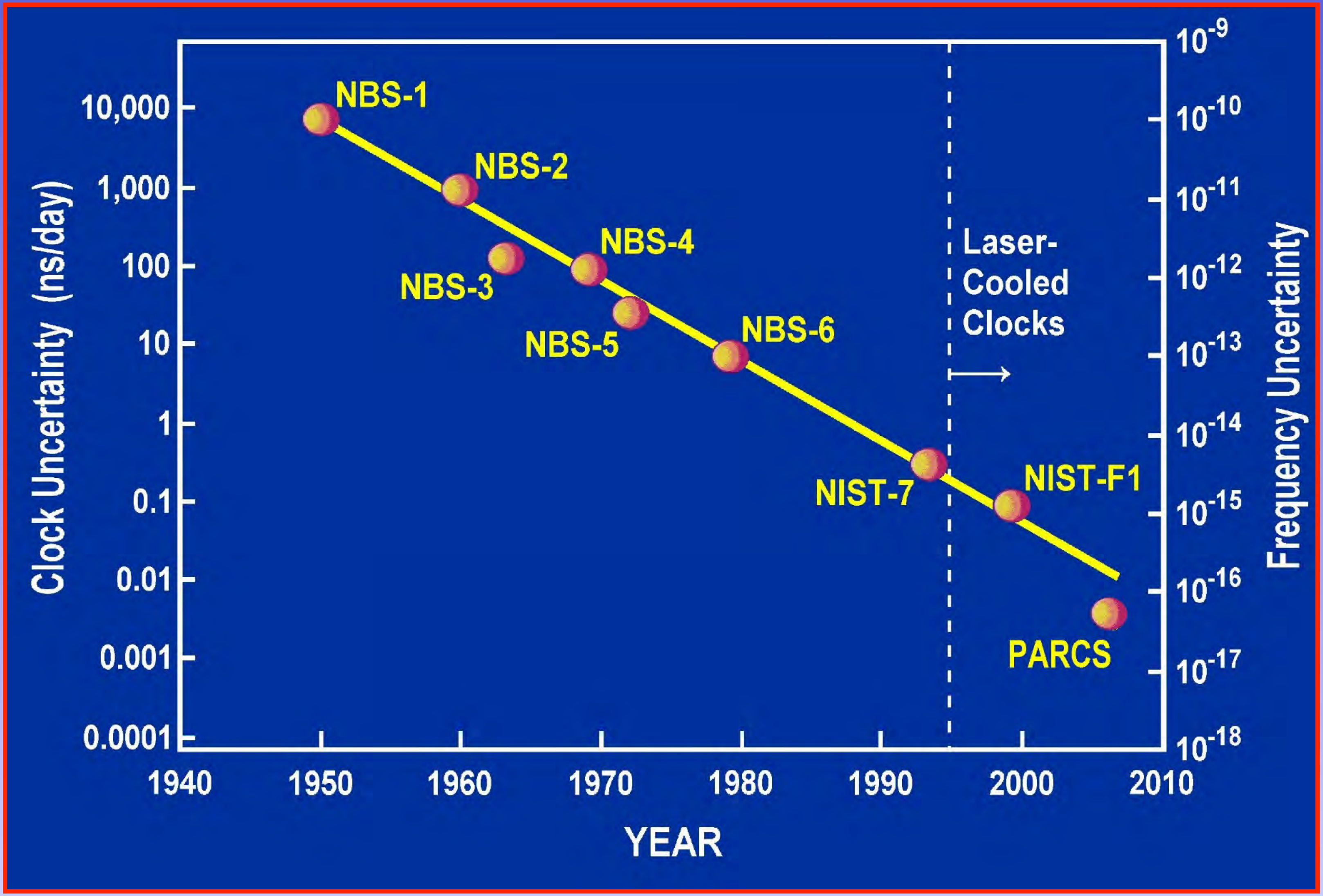


NIST-7

NBS-6



NIST Standards vs Time



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Atomic Line Q

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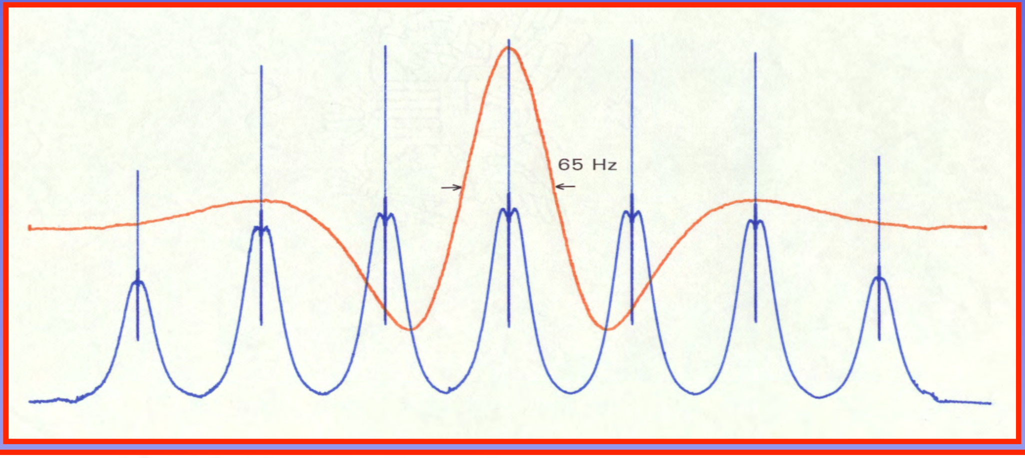
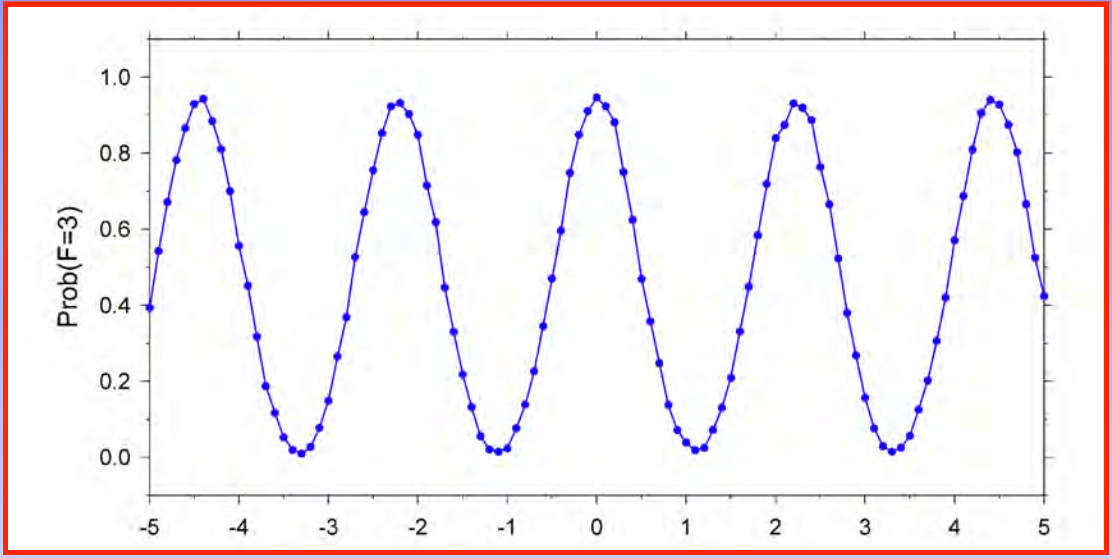
- Increase The Frequency of the Clock Transition
- Improve the S/N

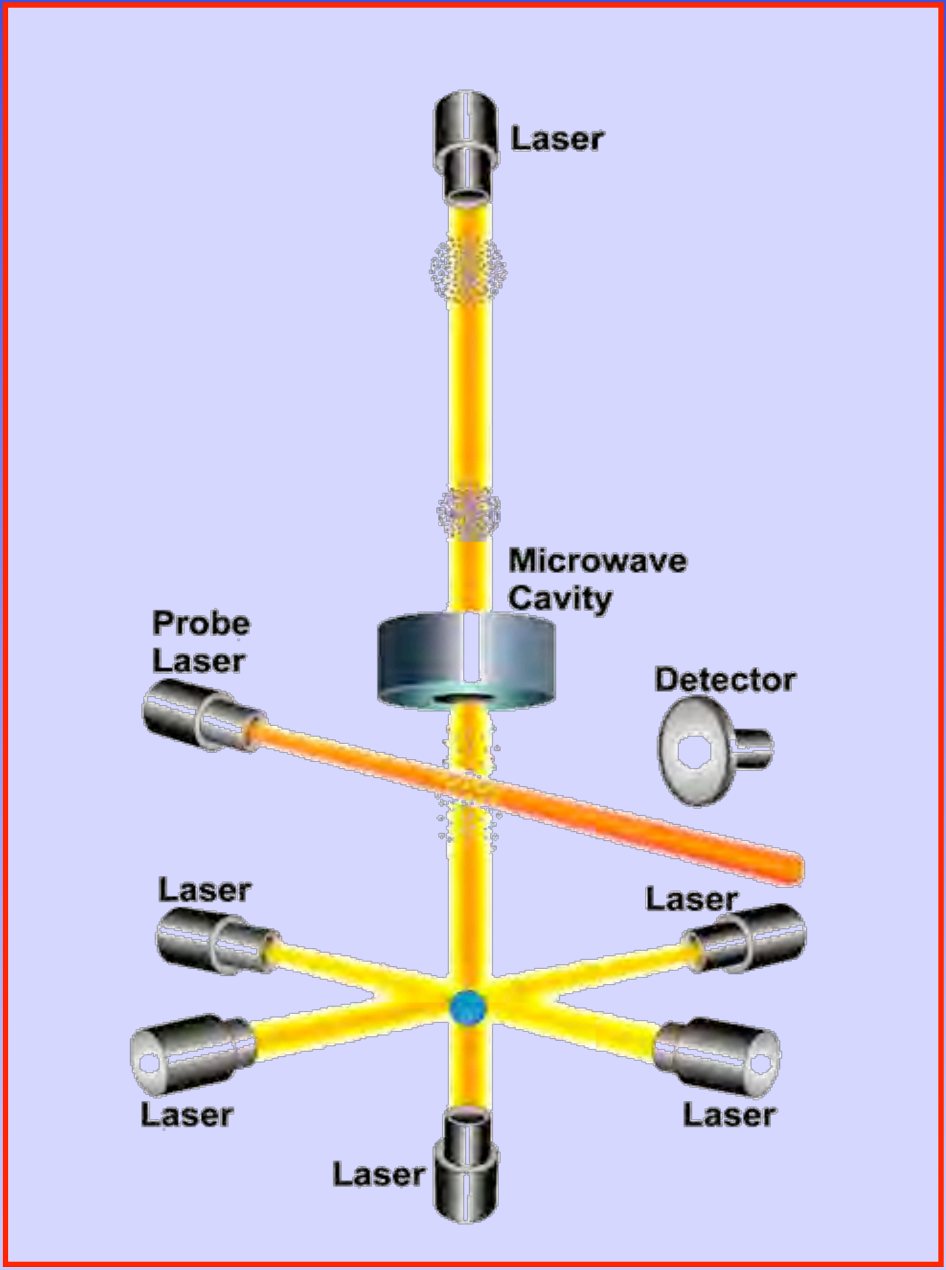
Ramsey Resonance in NIST-7 and NIST-F1



NIST-7



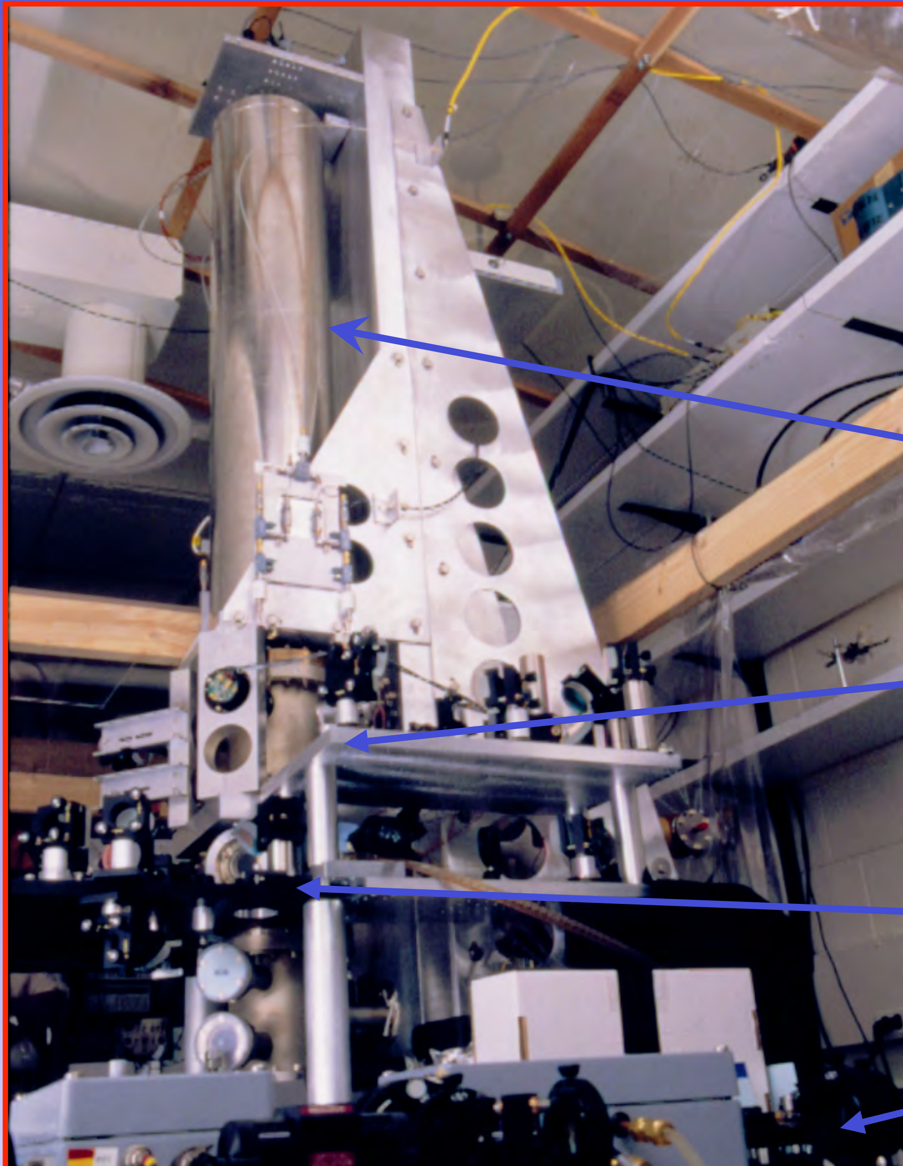
NIST-F1



Description of Cesium Fountain

U.S. Primary Frequency Standard

NIST-F1



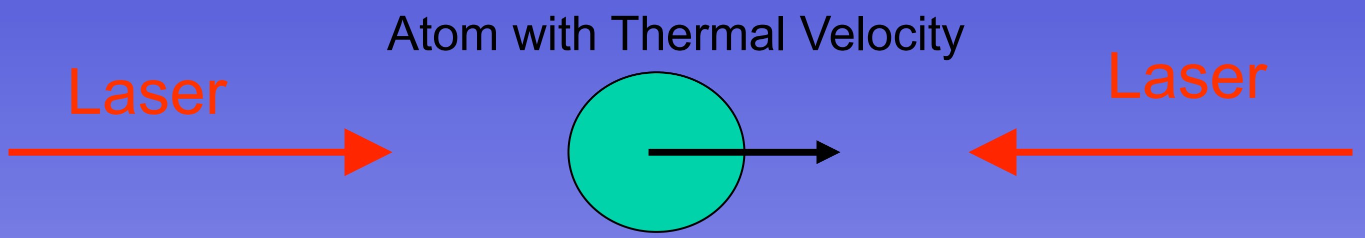
Magnetic Shields: Microwave Cavities and Flight Tube are Inside

Detection Region

Cs Optical Molasses Region

Optical Bench: Lasers, etc.

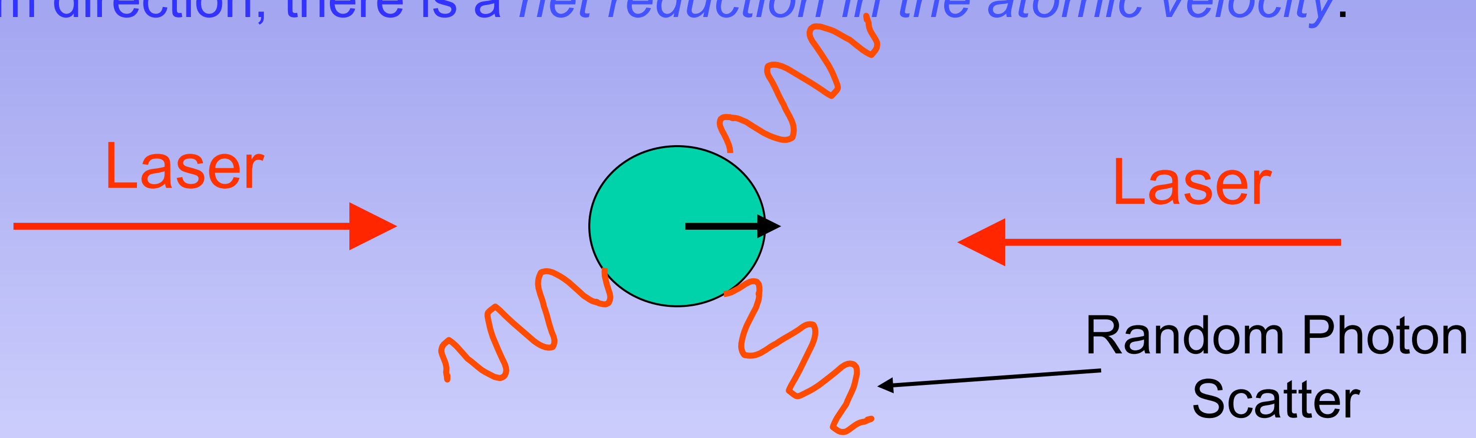
Laser Cooling of Atoms



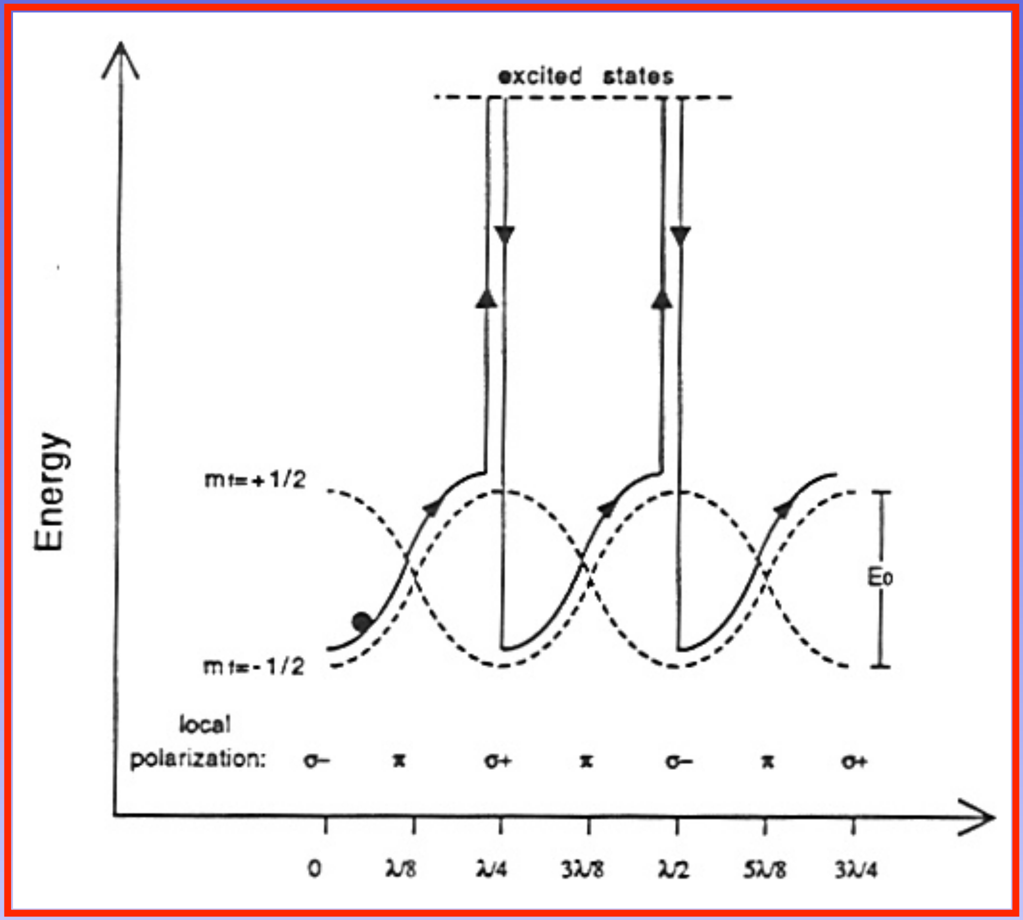
Laser Frequency is tuned slightly below the atomic resonance:

$$\omega_{laser} = \omega_{atom} - \delta$$

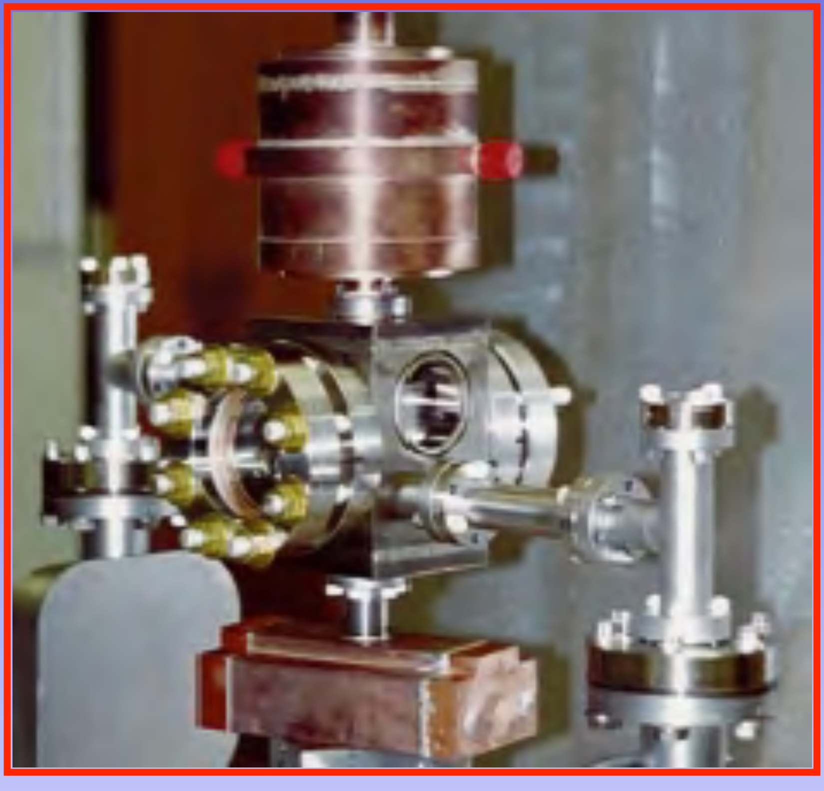
The atom is Doppler shifted into resonance with the laser beam on the right and thus absorbs photons from only this beam. Each photon *transfers momentum* ħ**k** to the atom. Since the subsequent photon emission is in a random direction, there is a *net reduction in the atomic velocity*.

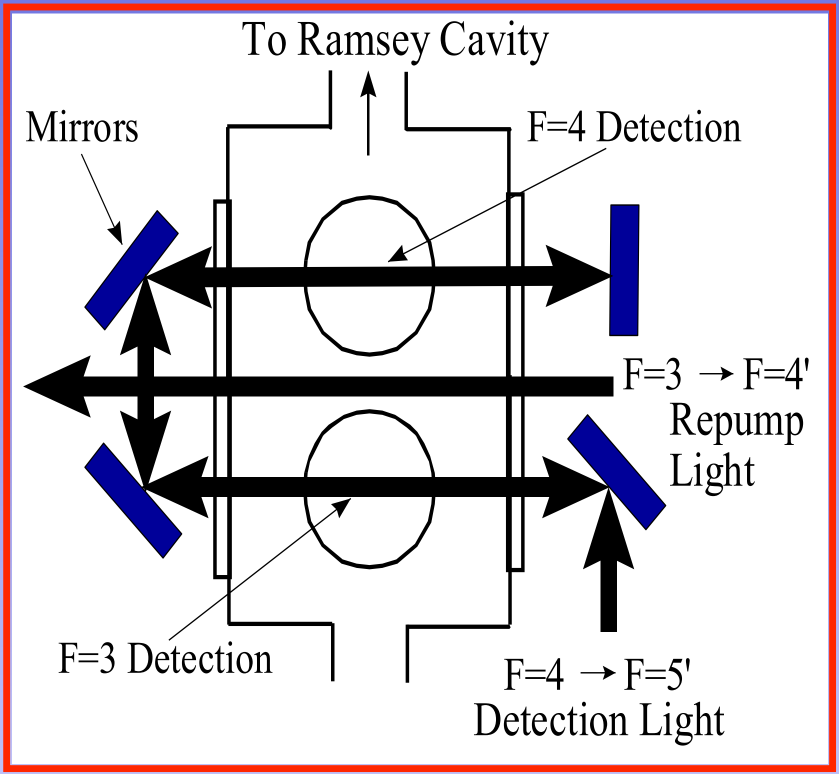


Laser Cooling - molasses

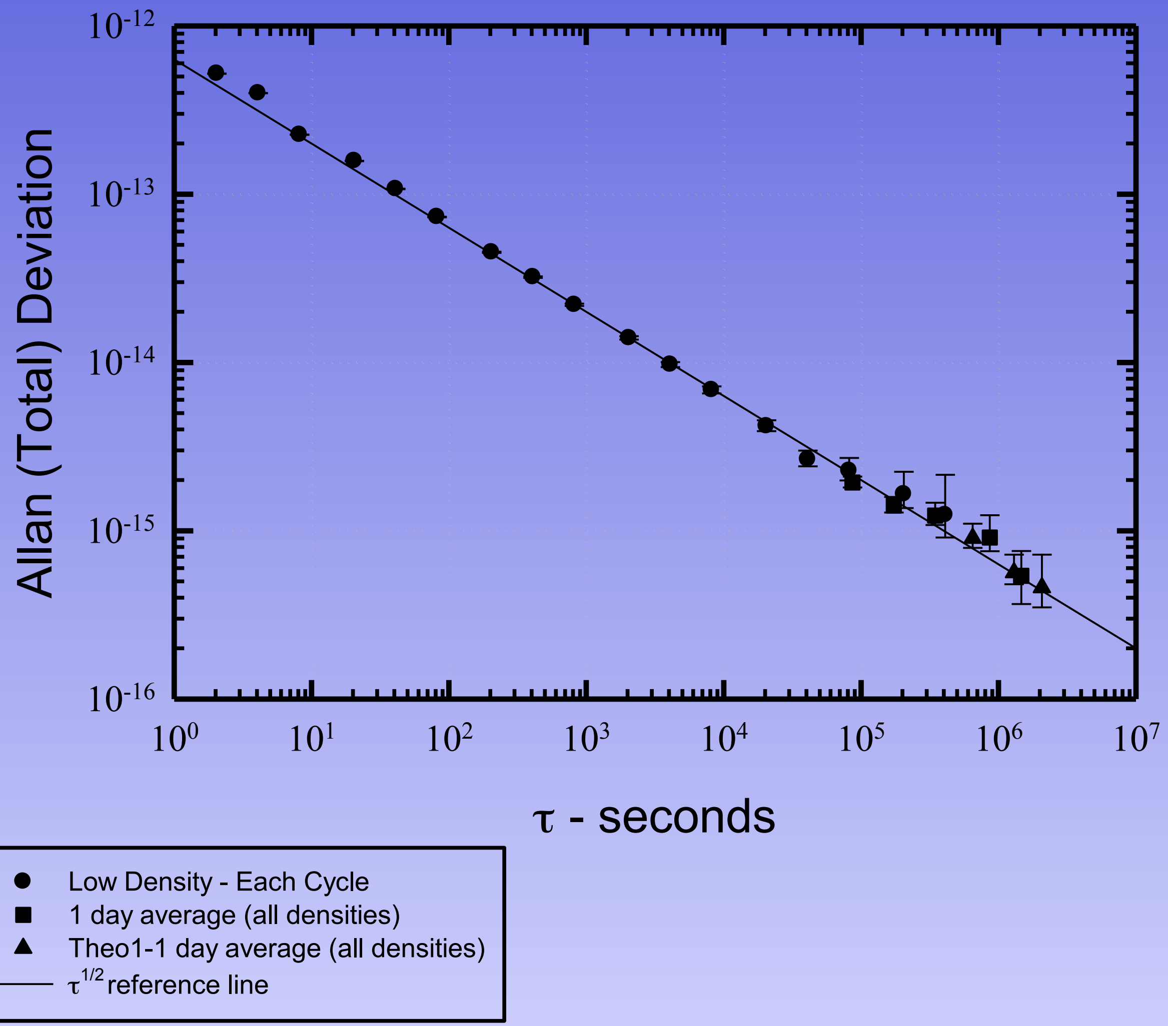


Detection Region





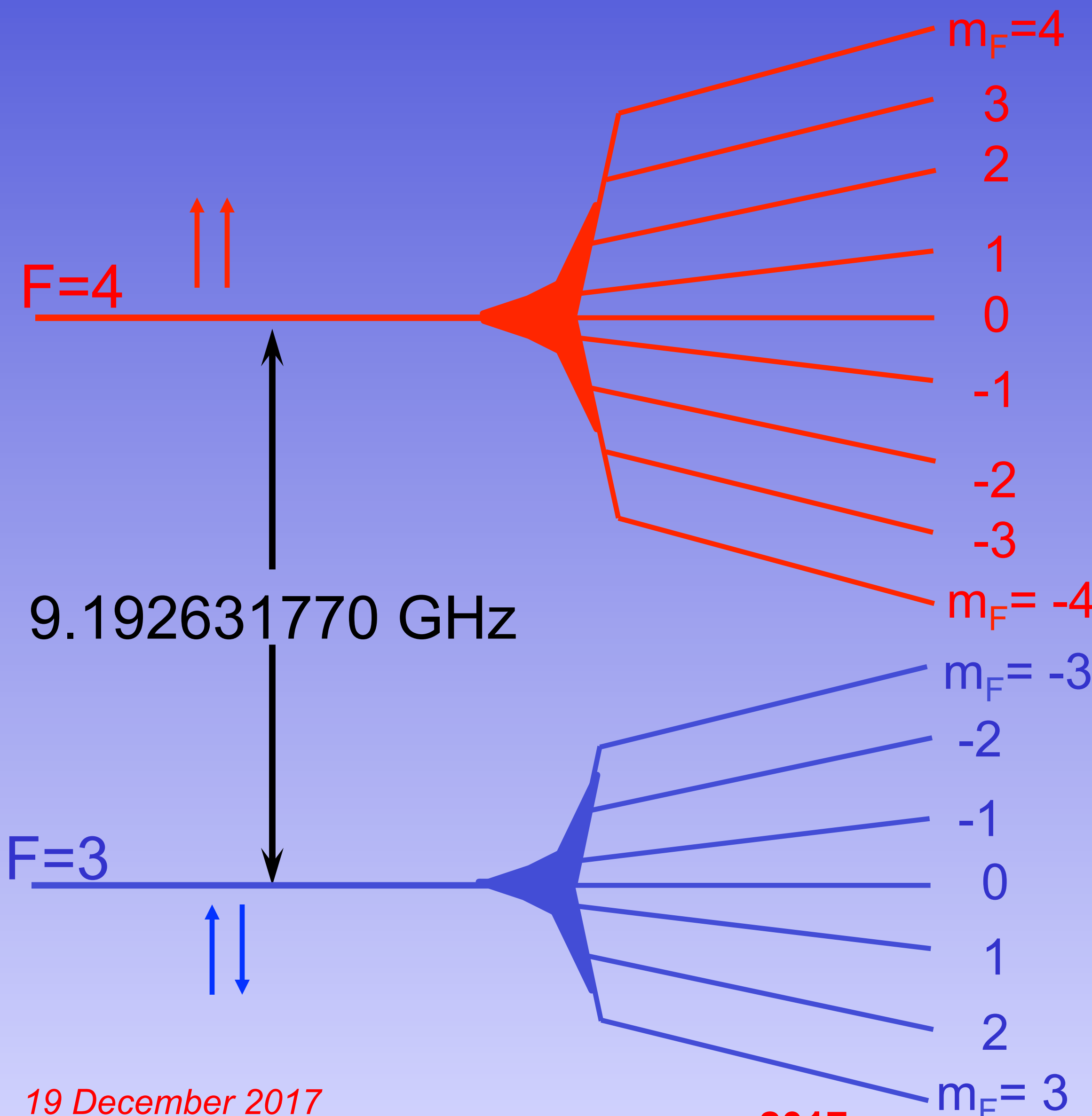
NIST-F1 measured total deviation $\sigma_T(\tau)$



Error Budget

Physical Effects	Bias Magnitude (×10^{-15})	Type B Uncertainty
• Second Order (quadratic) Zeeman	+44.76	0.02
• Second Order Doppler	<0.1	<0.1
• Cavity Pulling	0.0	0.02
• Rabi Pulling	0. 0	0.0001
• Cavity Phase (distributed)	0.02	0.02
• Fluorescent Light Shift	0.00001	0.00001
• Spin Exchange	0.0 * (0.4-4)	0.1
• Blackbody	20.6	0.26
• Gravitation	+180.54	0.03
Electronic Shifts		
• R.F. Spectral Purity	0	<0.003
• Integrator Offset	0	0.1
• Microwave leakage	0	0.2
Total Type B Uncertainty		**0.36**

Zeeman

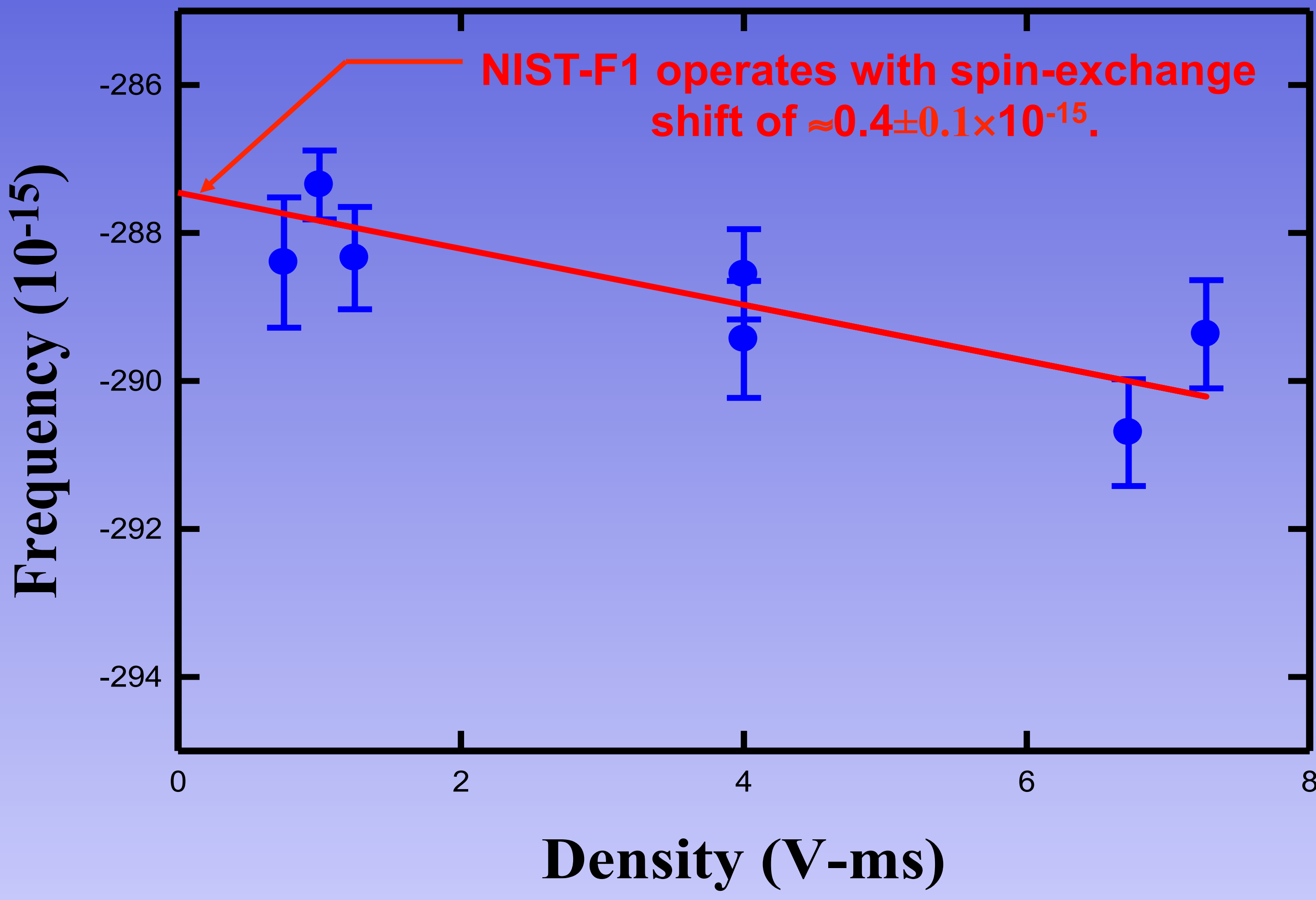


- (3,0)-(4,0) frequency is the "clock" transition
- (3,1)-(4,1) transition shifts by 701 kHz/gauss, we use this to measure the magnetic field
- The (3,0)-(4,0) clock transition shifts by 427.45 Hz/gauss2
- In NIST-F1 the field is 0.85 mGauss and the shift is $\sim 2\times 10\uparrow -13$

Blackbody

- Radiation associated with non-zero temperature peak at about 10μm
- Frequency shift is relatively large $\sim 2 \cdot 10^{-14}$
- Shift is about $3 \cdot 10^{-16}$/°C!
- Temperature Uncertainty is mainly due to leakage of room temperature radiation
- Final Uncertainty is Assigned 1C ~ $\delta f/f = 3 \cdot 10^{-16}$

Density Extrapolation



Gravity

- Relativistic Effect…the higher above the reference geoid you go, the faster the clock runs…..the shift is about 10^{-16}/m. This shift is $2 \cdot 10^{-13}$ in Boulder!!!!
- With care, the correction is good to less than 10^{-16}.
- The reference geoid is approximately mean sea level.

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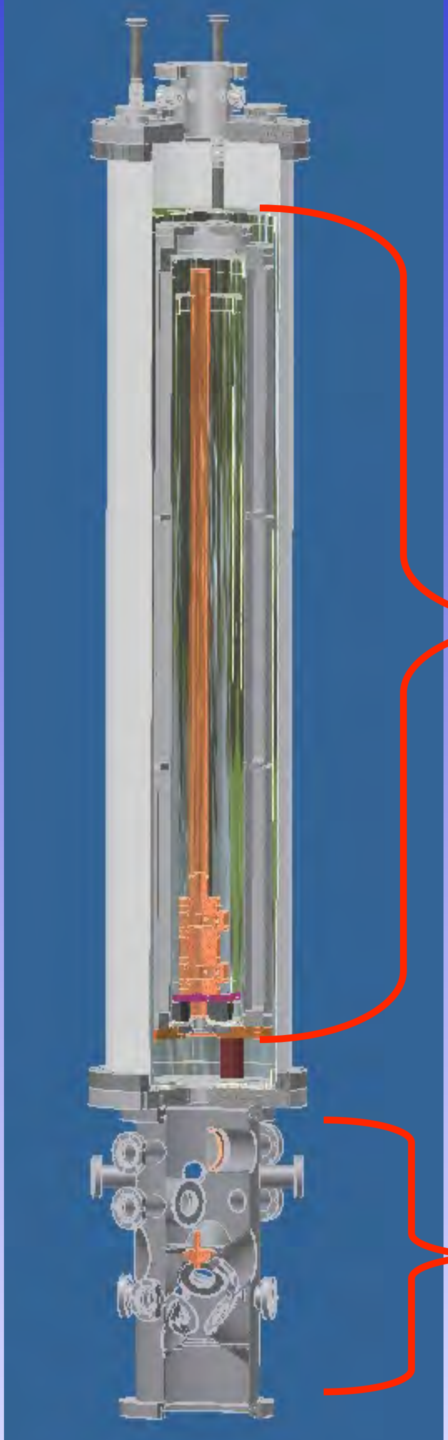
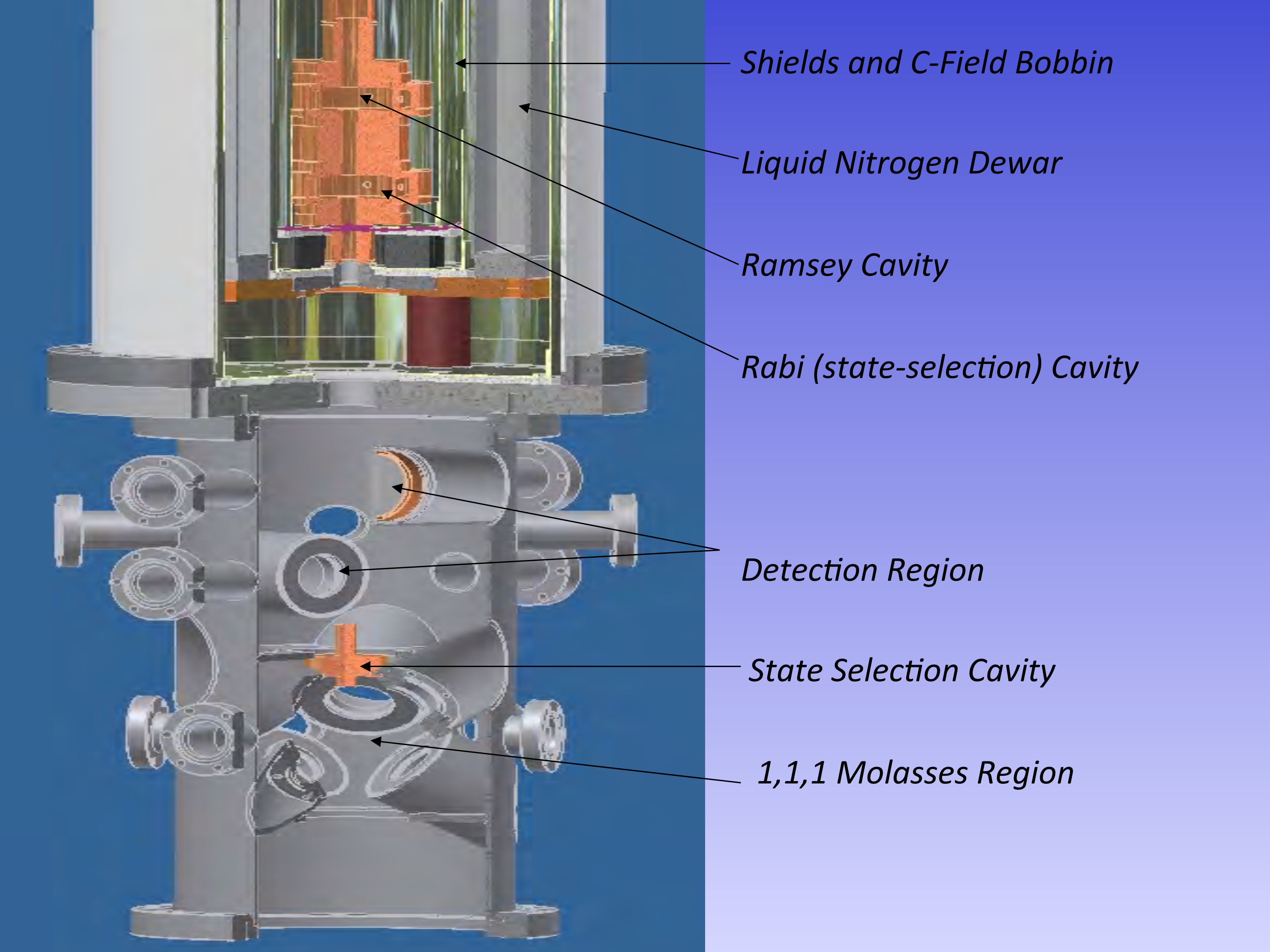
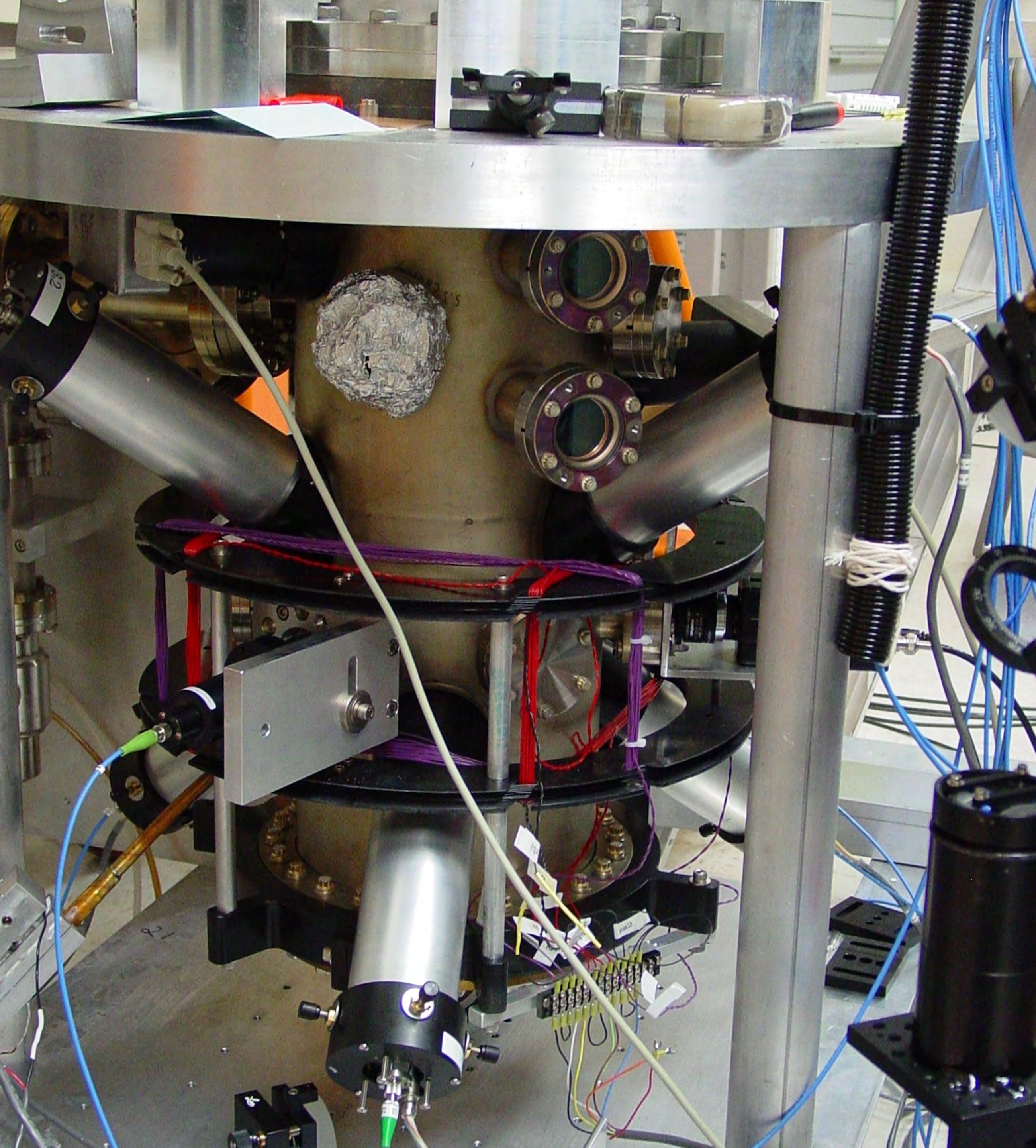
NIST-F2 Physics Package



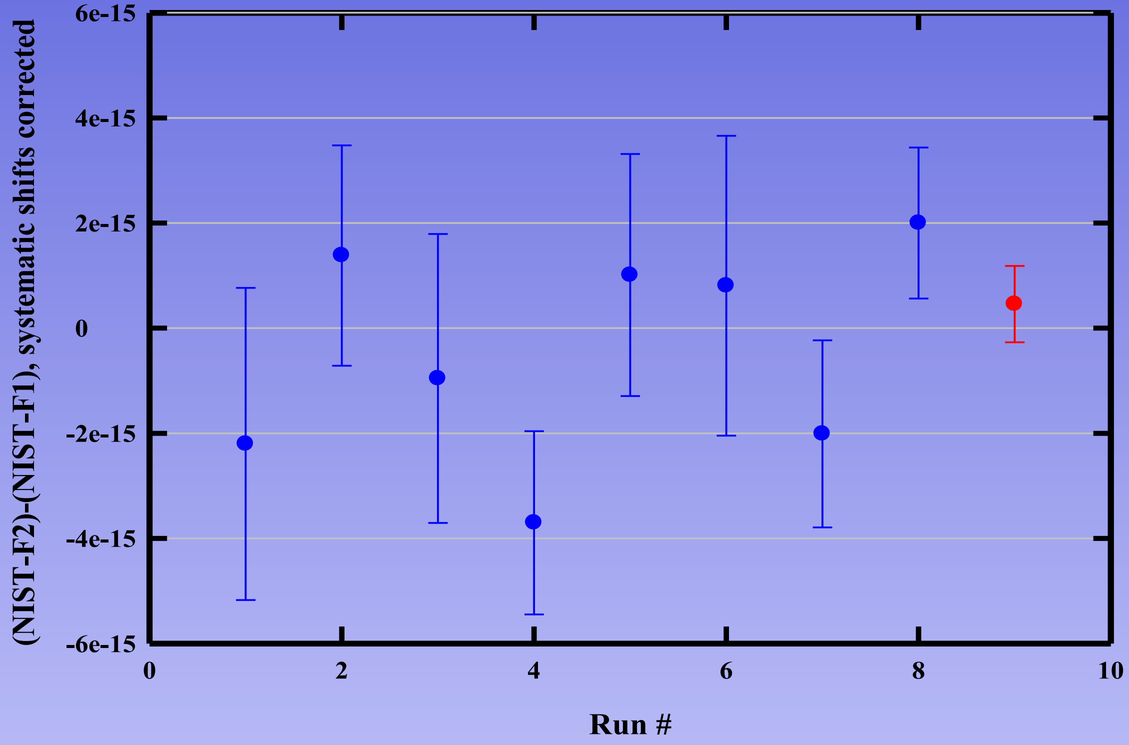
Cryogenic (80K) Region with
Ramsey microwave cavity C-field, magnetic shields and drift region

Room temperature molasses collection and launch region with detection region above molasses region


Shields and C-Field Bobbin
Liquid Nitrogen Dewar
Ramsey Cavity
Rabi (state-selection) Cavity
Detection Region
State Selection Cavity
1,1,1 Molasses Region



NIST-F2 vs. NIST-F1 – a measurement of the Blackbody Shift

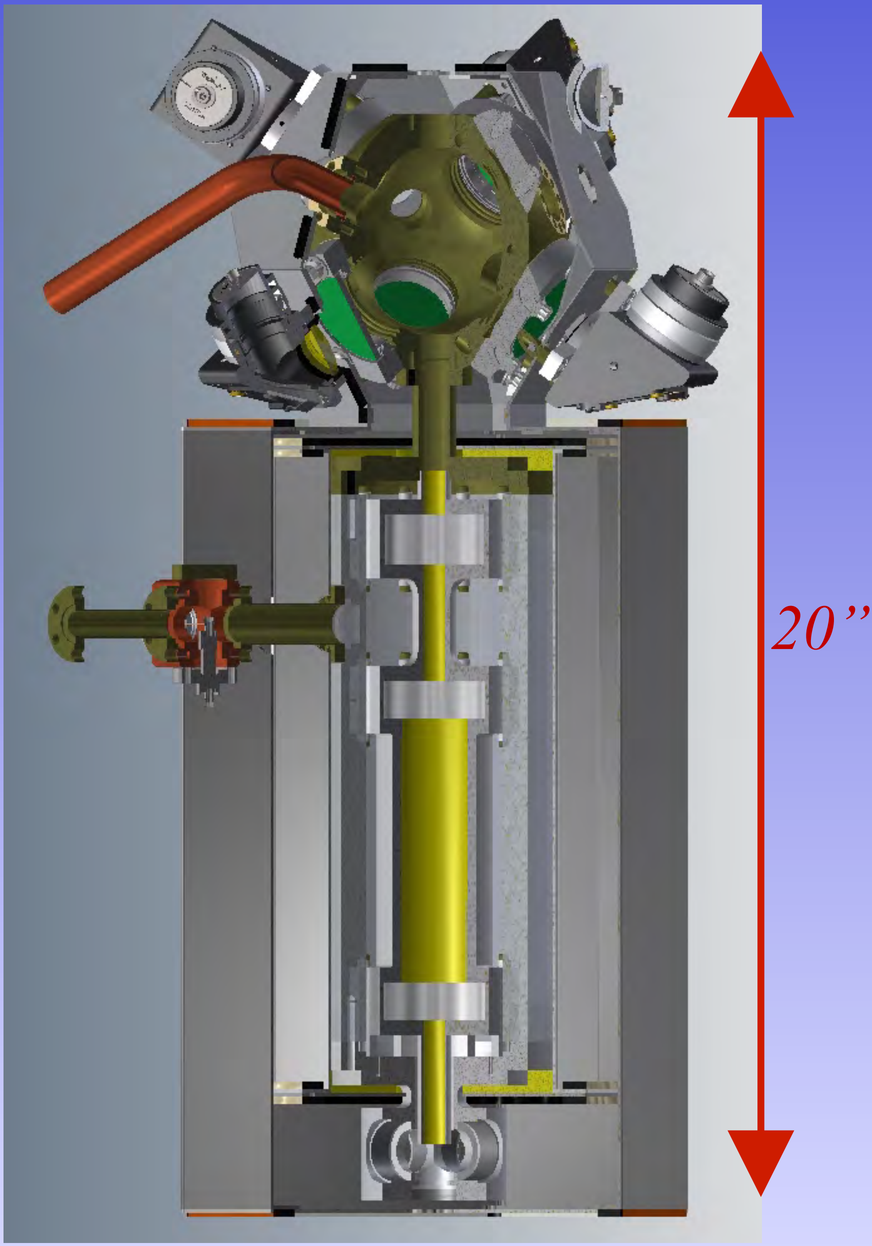


The data shown in blue are the individual runs since pressure control on the dewar. The final point (in red) is the average of all runs. F1 is corrected for blackbody, Zeeman and spin-exchange, F2 is corrected for spin-exchange and Zeeman.

How Do We Do Better ?

- Work Harder on Earth – possible, but difficult, no matter how hard we work Ramsey times will be limited to ~1 s
- Go into Space – no gravity allows long Ramsey times – better accuracy

Physics Package – Parabolic flight

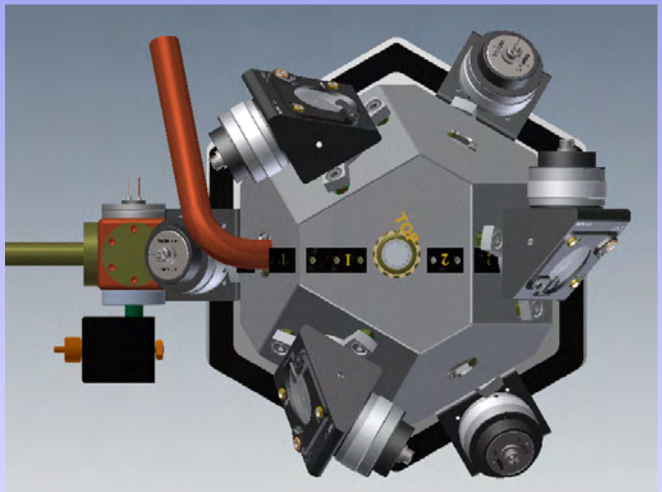


This is the entire physics package with pumping

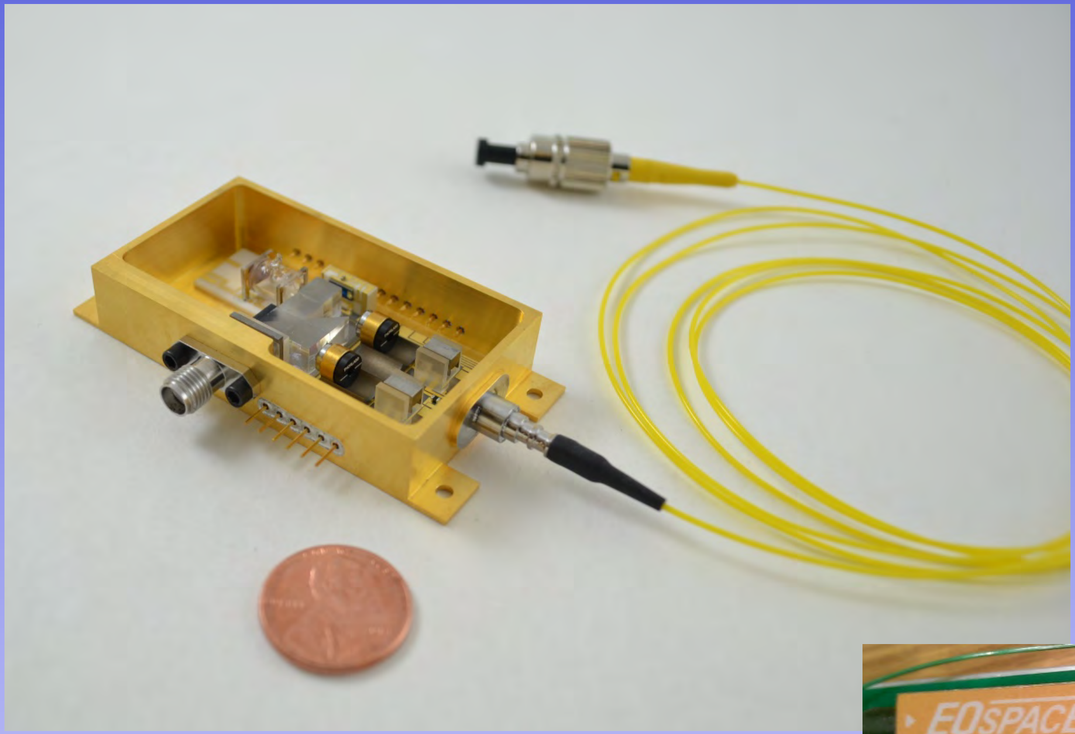
All specialized vacuum parts (e.g. windows, seals etc are COTS)

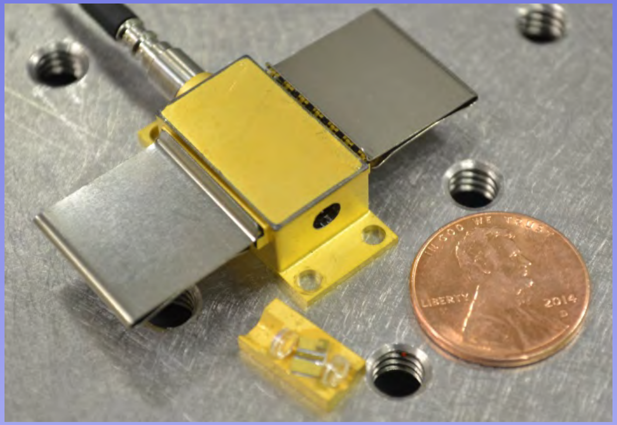
Source region can be made much smaller with custom pieces

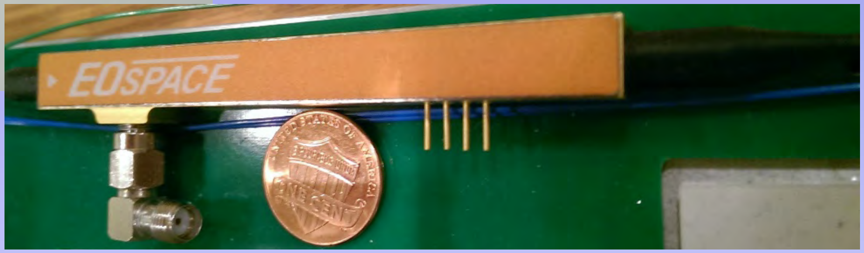
Ramsey Interaction zone has 2 layers of magnetic shielding – all of the clock has at least one layer.



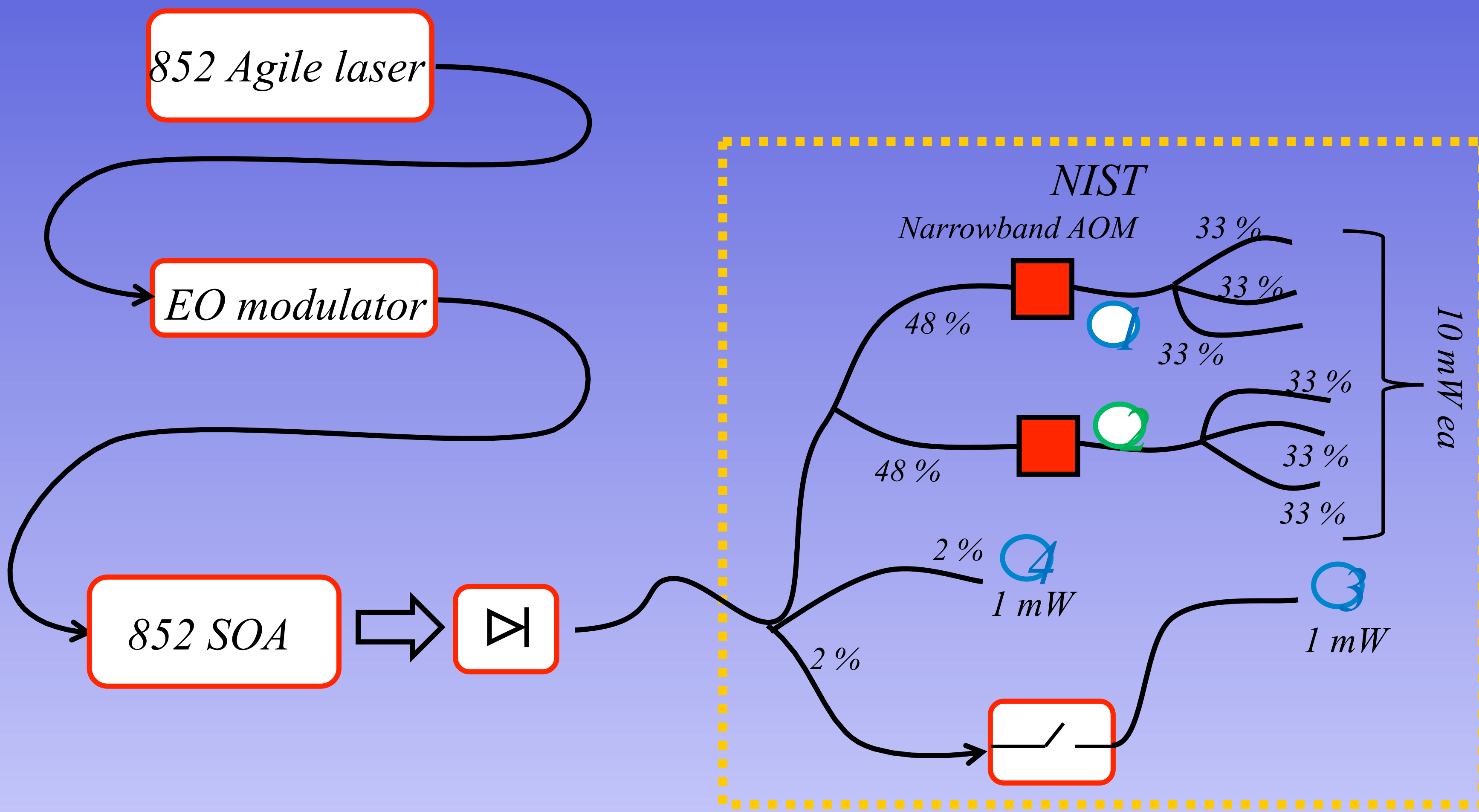
Vescent Laser System for AFRL/NIST cold Cs. Clock



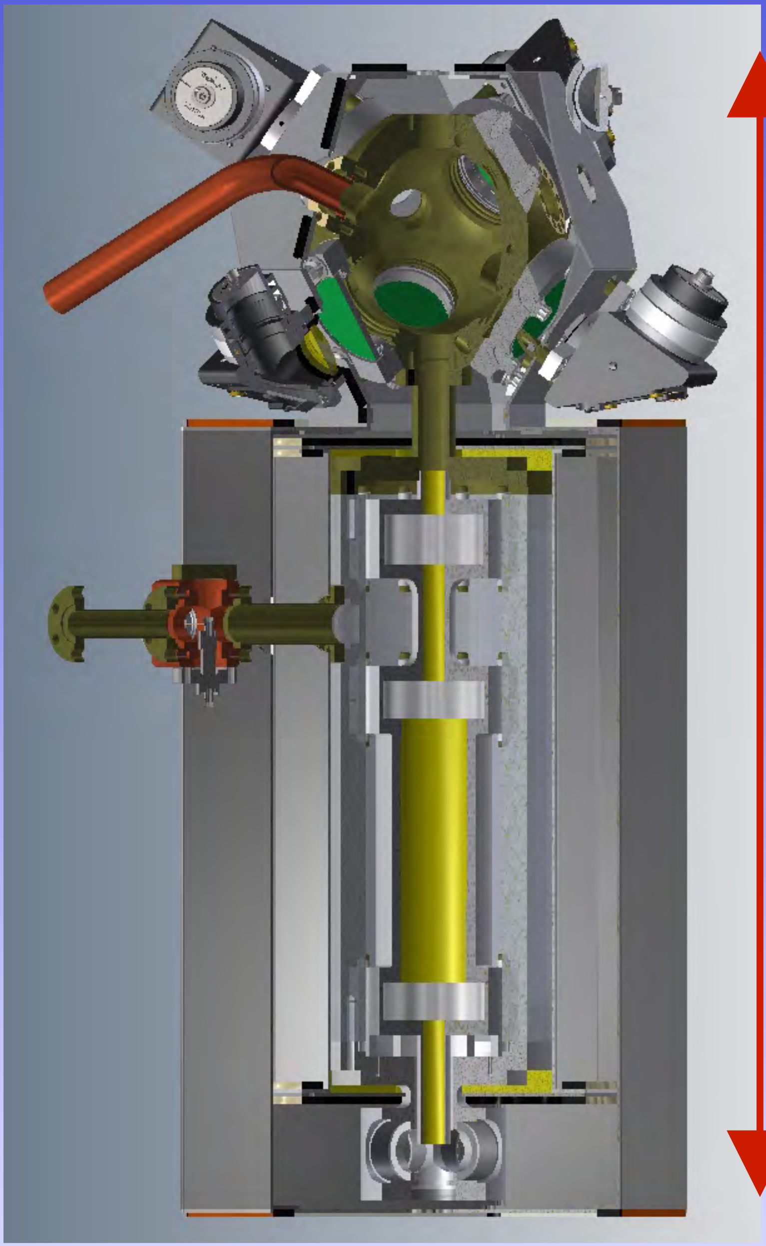




Laser Beam delivery Schematic Diagram



Physics Package – Parabolic flight



20”

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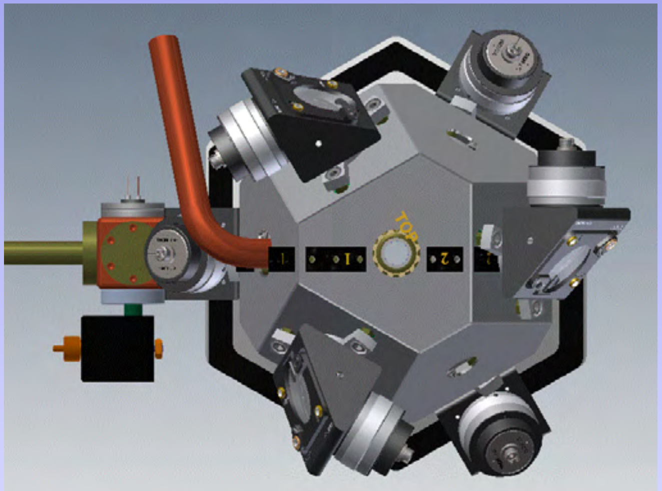
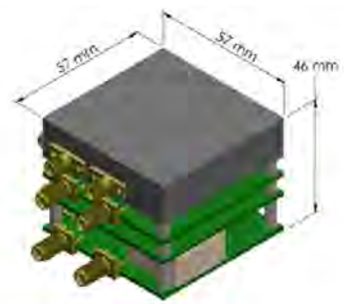


Microwave Synth & Quartz



Miniature 9.192 GHz Synthesizer	
Metric	Specification
Size	0.25L
Weight	0.3kg
Power	4W

SPECIFICATIONS

PARAMETER	CONDITIONS	TYP	MAX	UNITS
Frequency Stability $\sigma_y(t)$	Averaging time			
	1 s	$3\cdot10^{-13}$		
	10 s	$8\cdot10^{-13}$		
Free Running	100 s	$3\cdot10^{-12}$		
Phase Noise L(f) *	Offset frequency			
	1 Hz	-57	-55	dBc/Hz
Carrier 9.192 GHz	10 Hz	-84	-82	
	100 Hz	-95	-93	
	1 kHz	-120	-117	
	10 kHz	-123	-120	
	100 kHz	-125	-120	
	1 MHz	-140	-135	
Phase Noise L(f)	Offset frequency			
	1 Hz	-117	-115	dBc/Hz
Carrier 10 MHz	10 Hz	-145	-143	
	100Hz	-157	-155	
	1 kHz	-162	-160	
	10 kHz	-170	-168	

Stability above is based on one quartz

5 selected quartz oscillators together give sufficient headroom to avoid Dick-effect at $\sigma_y(\tau)=2\times10^{-13}/\sqrt{\tau}$.

Will require an additional 1.2 W or so.

MK III Physics Package

GPS MK 3 Vacuum Chamber

- Cavity, cavity nipple and detection region will be made of aluminum. Ti shown in green, Cu in Cu color.

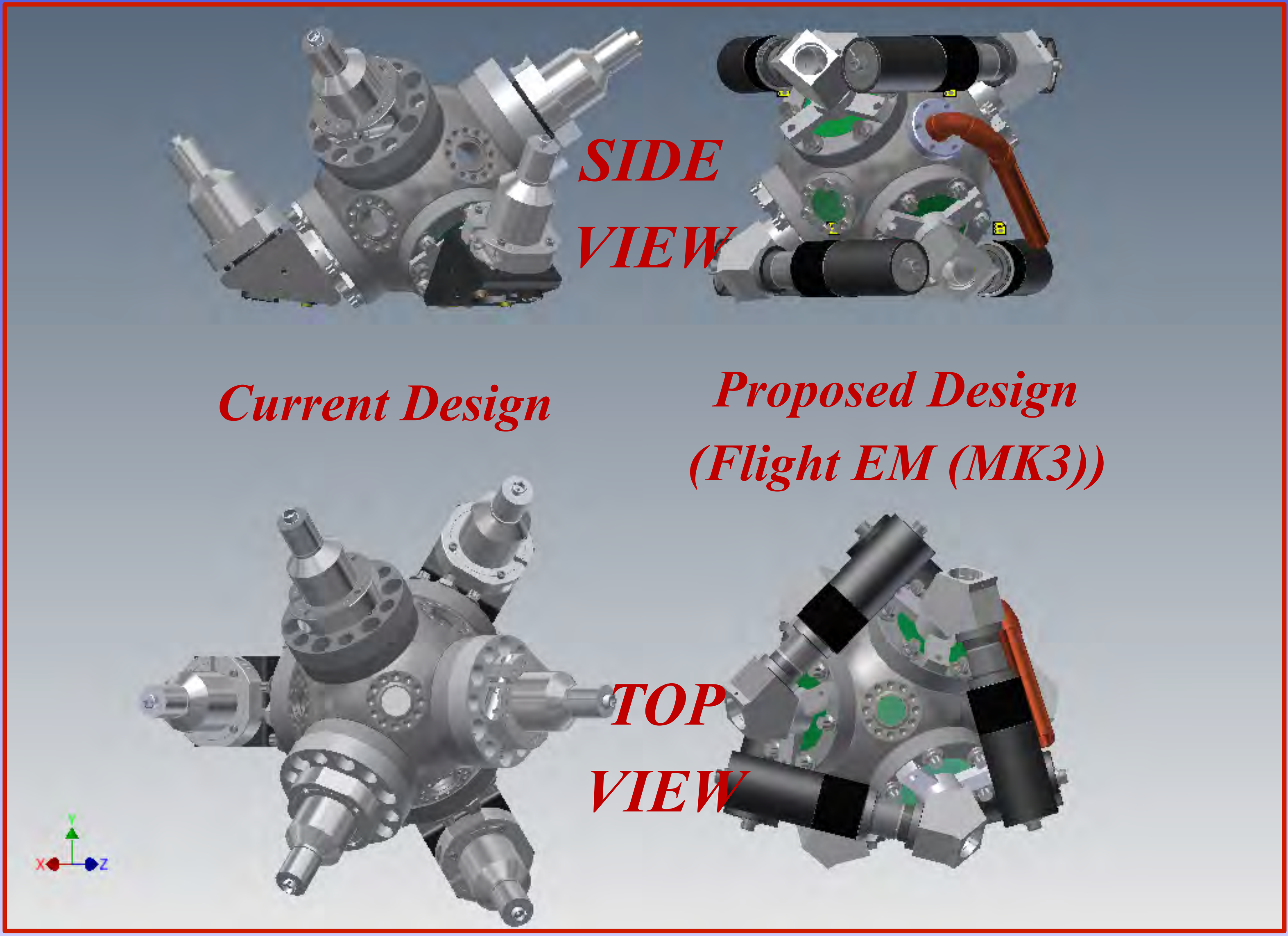
GPS MK 3 w

- Titanium Molasses Chamber
- Titanium Window Flanges

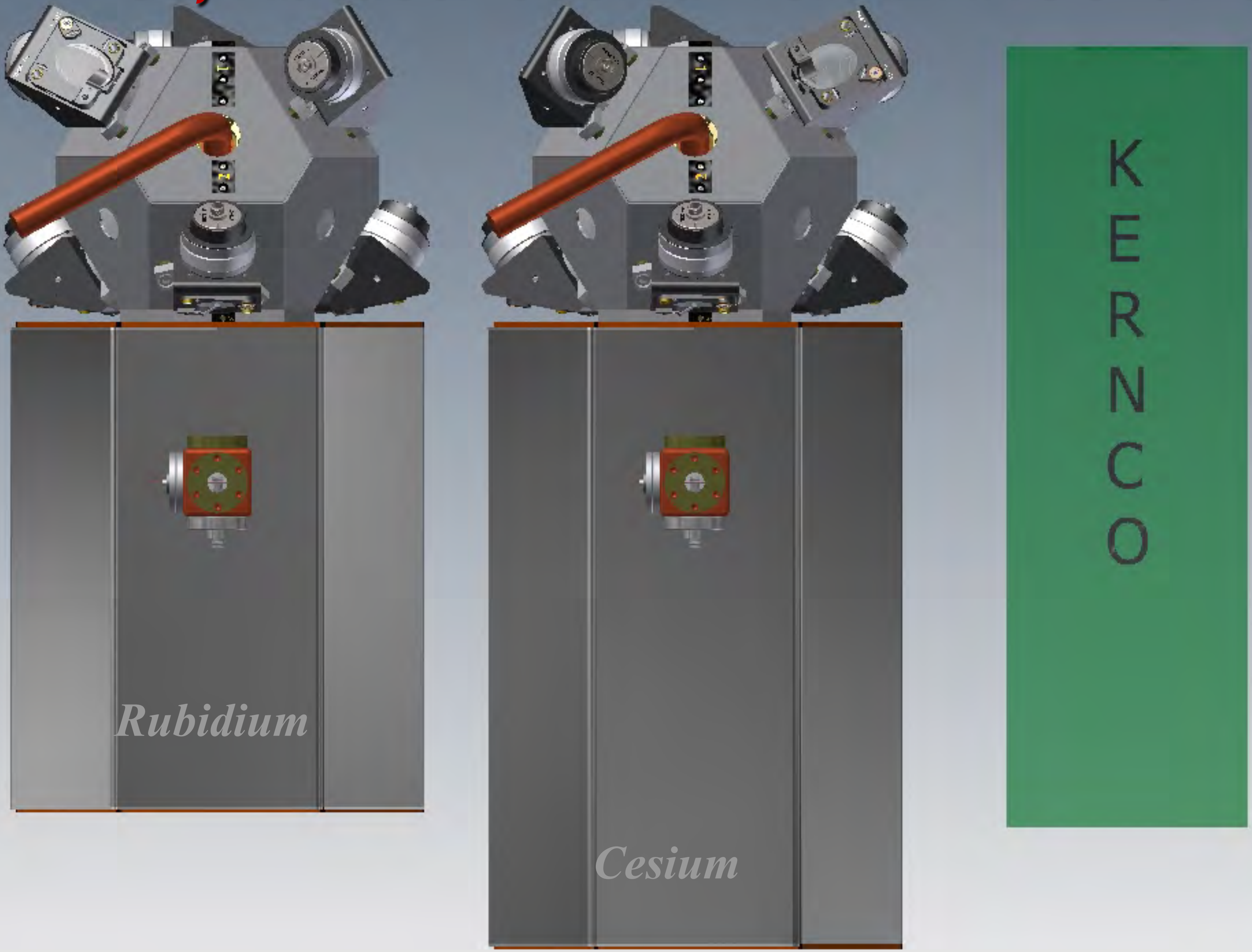
GPS MK3 unmounted, no detection optics

- Miniature Vacuum pump on left side
- Shielded Molasses chamber
- Folded Collimators

Source Region



Cs, Rb laser-cooled vs. KERNCO GPS



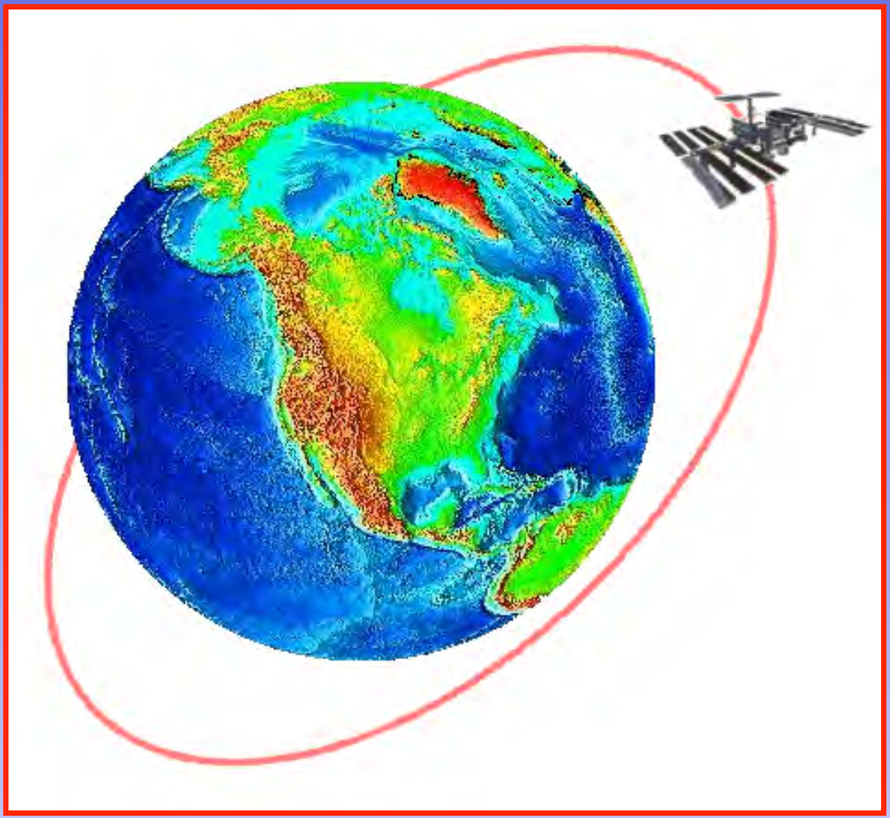
Predicted Performance

- Assumes Atom Shot Noise limit and removal of 14 cm of length on current design (we believe that 20 cm reduction is achievable, 14 cm is obvious).
- Assumes 4 additional quartz oscillators at 300 mW and 8 cm^3 each.
- Clock cycle time is 0.5s and Ramsey is 0.18s

$$\sigma_y(\tau)=\frac{1}{T_R\,\omega_o}\,\frac{1}{\sqrt{2N}}\,\sqrt{T_C/\tau}$$

This gives $\sigma_y(\tau)=2.1\times 10^{-13}/\tau^{1/2}$ for a very conservative atom number of 5×10^{4} (we see 10x this in the lab routinely).

Scientific Goals



- Relativistic Frequency Shift
- Gravitational Frequency Shift
- Local Position Invariance Test
- Realization of the Second
- Studies of the Global Positioning System

How Do We Do EVEN Better ?

- Microwave Standards probably limit in the $\delta f/f \sim 5 \cdot 10^{-17}$ level ….. Then What?
- Remember $\sigma \propto \dfrac{1}{Q(S/N)} = \dfrac{1}{(\omega/\Delta\omega)(S/N)}$

SO.. Make ω bigger!

Neutral Optical Clocks

$$\sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

10^{15} Hz

Image of Trapped Ca Atoms:
Optical Clock at 657 nm is based on a narrow transition in neutral calcium.

New techniques are now available for optical-to-microwave comparisons.

*Oats, Hollberg, Optical Frequency Measurements Group, Time and Frequency Division, NIST

Ion Trap Clocks

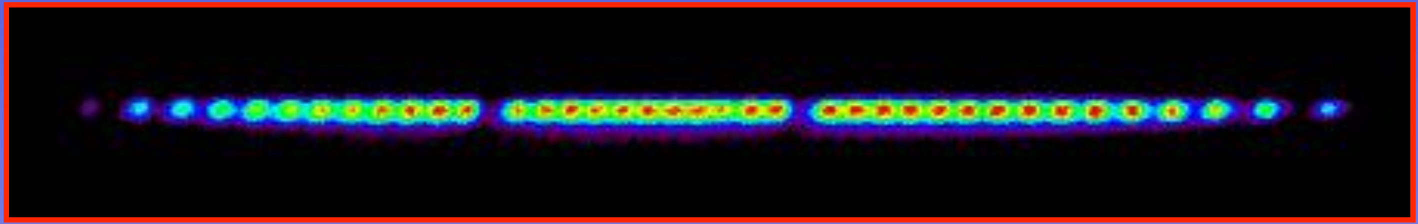
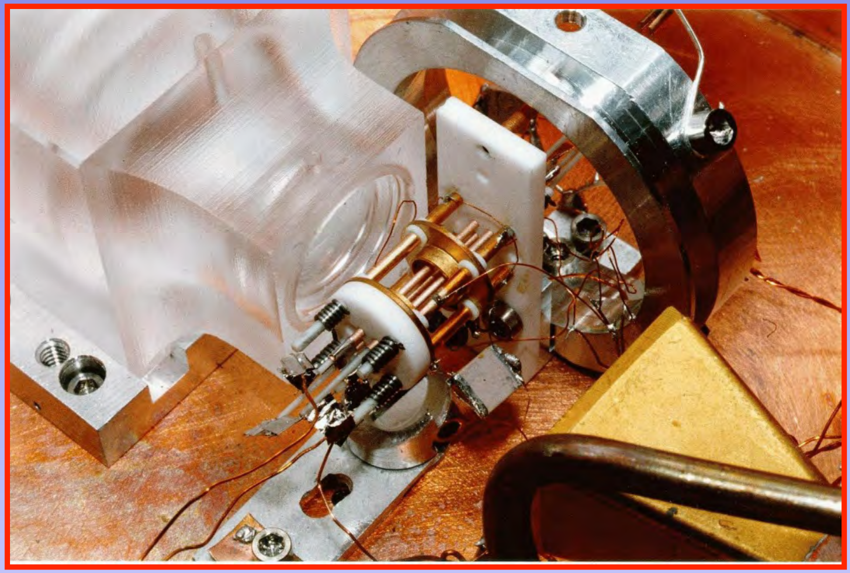


Image of Trapped $^{199}Hg^{+}$ Ions

Linear RF Ion Trap



Ion Traps:

- Long Ramsey Times (100 s)
- Small Trapping Volume (Lamb-Dicke Regime)
- 40.5 GHz Transition
- Optical Transition at 282 nm (10^{15} Hz)

* Bergquist, Itano, Bollinger, Wineland, Ion Storage Group, Time and Frequency Division NIST

Conclusions

- *Laser-Cooling for Frequency Standards allows higher accuracy in both microwave and optical clocks*
- *Cesium Primary Frequency Standards fulfill present and foreseeable future needs up to* $\delta f/f = 10^{-16}$ *or so*
- *Future (>10years) Primary frequency standards will probably be based on optical transitions.*