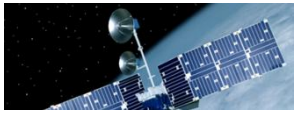
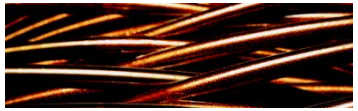
Principles of Atomic Clocks





EFTF – IFCS 2011 Tutorial

May 1, 2011 San Francisco, CA

Robert Lutwak

Symmetricom - Technology Realization Center

RLutwak@Symmetricom.com

Tutorial Overview

- This tutorial covers "industrial" atomic clocks
  - "Clocks you can buy"
  - Conventional Atomic Clocks
    - Cesium beam frequency standards, Rubidium Oscillators, Hydrogen Masers
  - New and emerging Atomic Clocks
    - CPT clocks, Chip-scale atomic clocks

- This tutorial ***does not*** cover "advanced" atomic clocks
  - "Clocks you have to build"
  - Laboratory-scale microwave clocks:
    - Cold-atom fountains and beams, ion clocks
  - Optical clocks:
    - Atom-stabilized lasers as frequency standards

Outline

- General things about clocks
- What is an atomic clock?
- Conventional Atomic Clocks
  - Cesium beam frequency standard (CFS)
  - Rubidium oscillator (RBO)
  - Hydrogen maser
- New and emerging atomic clocks
  - Coherent-population trapping (CPT)
  - Chip-Scale Atomic Clock (CSAC)

General Things about Clocks

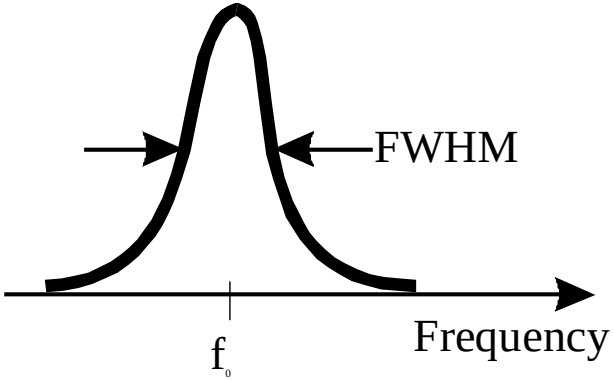
What is a Clock ?

+

=

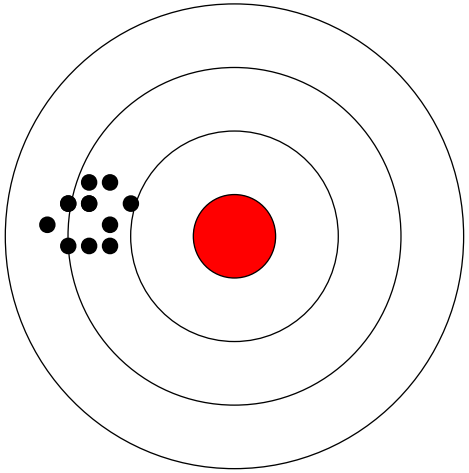
(Oscillator + Counter = Clock)

<u>Everything is an Oscillator</u> *(but some things make better clocks)*

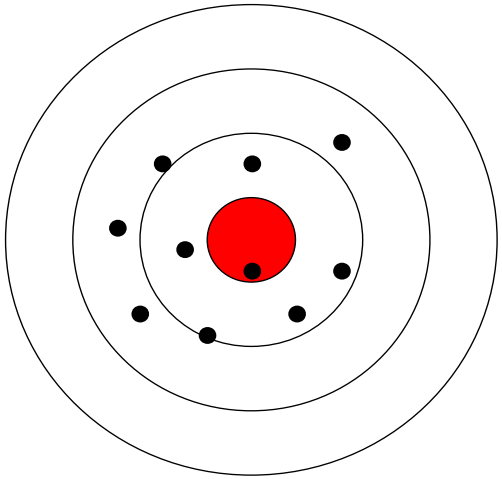


$$Q = \frac{\text{Resonant Frequency}}{\text{linewidth (FWHM)}} = \frac{\text{Ring-down Time}}{\text{Period}}$$

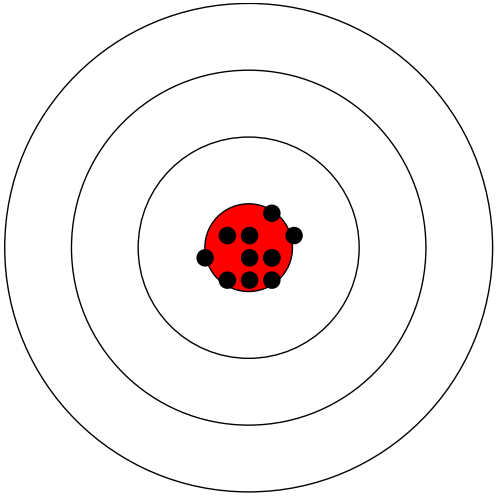
Accuracy and Stability



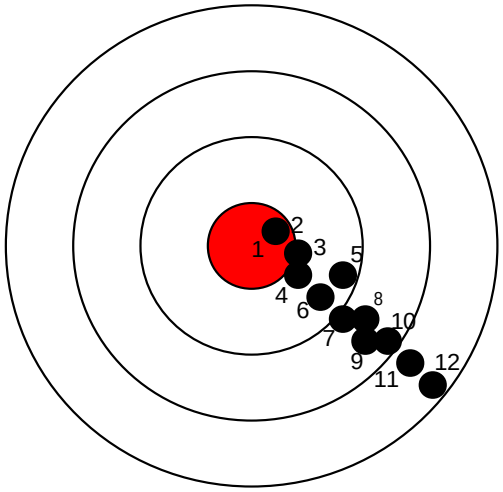
Stable but not Accurate



Accurate but not stable

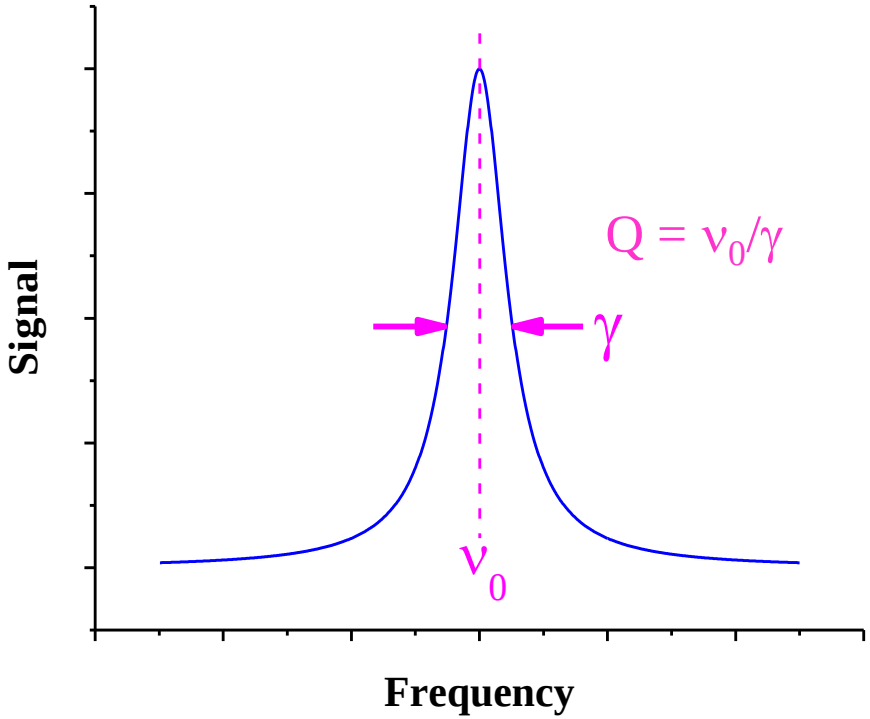


Stable and Accurate



Stable and Accurate but drifting

Clock (in)Stability



Equation 1 (of 1):

$$\sigma(\tau = 1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$

- ν_0 is resonance frequency
- γ is linewidth
- $(S/N)_{1Hz}$ is Signal/Noise in 1 Hz bandwidth

  i.e. how well can we find the center of the line during the measurement time?

Applications

Symmetricom

- Seconds/day ($\approx 10^{-5}$)
  - "Human time" – wristwatches, computers, clocks, etc.

Quartz Oscillators

- Milliseconds/day ($\approx 10^{-8}$)
  - Lab instruments
  - Network communications (Tx/Rx)

Ovenized Quartz Oscillators (OCXO)
Temperature-compensated Quartz Oscillators (TCXO)

- Microseconds/day ($\approx 10^{-11}$)
  - Network sync - broadcasting, cell-phone towers, etc.
  - Time-keeping – data acquisition, financial markets
  - Laboratory timing - calibration, science & engineering
  - Navigation – Inertial nav, enhanced GNSS receivers
  - Security - Time-code encryption

Rubidium Oscillators (RbO)
Coherent Population Trapping (CPT) Clocks
Chip-scale atomic clocks (CSAC)

- Nanoseconds/day ($\approx 10^{-13}$)
  - Radio astronomy, deep-space communications
  - GNSS - (GPS, Galileo, Glonass, Compass, etc.)
  - Time-keeping – National laboratories and time-scales
  - Physics – high-precision measurement, general relativity

Cesium beam Frequency Standards (CFS)
Hydrogen Masers

What is an “atomic” clock ?

The first million hits on Google…

Symmetricom

About 1,070,000 results (0.11 seconds) Advanced search

Clocks Atomic at Amazon - Buy clocks atomi Ad
Qualified orders over $25 ship free
amazon.com is rated ★★★★★ (5,717 reviews)
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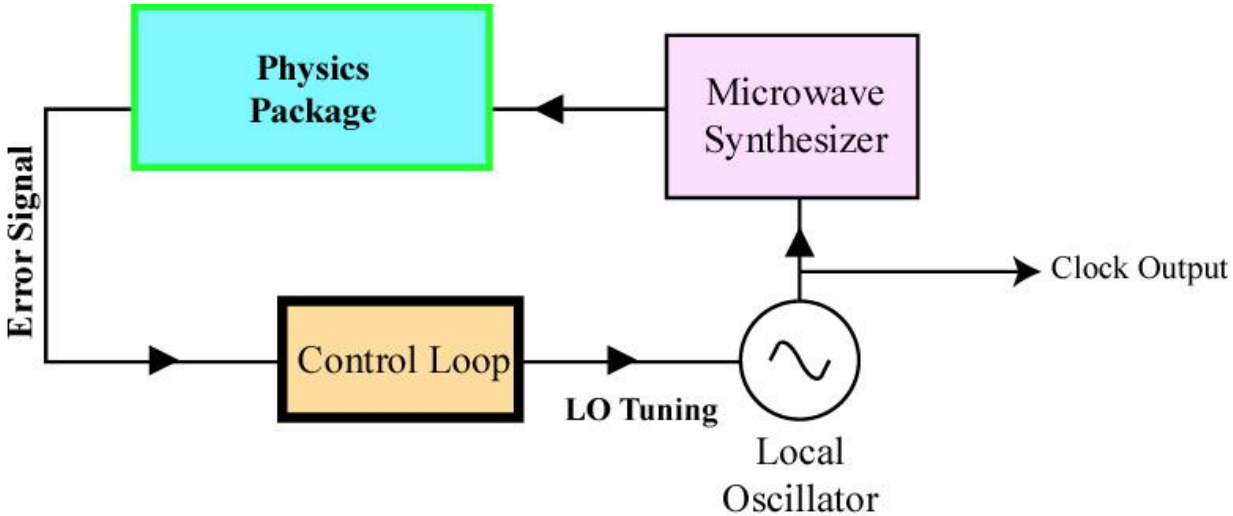
What is an atomic clock?



Local oscillator (LO) is typically (5 or 10 MHz) quartz oscillator

"Natural" atomic microwave resonance frequency is synthesized from LO.

Microwaves are applied to atoms in physics package

Physics package "error signal" is a measure of LO frequency error

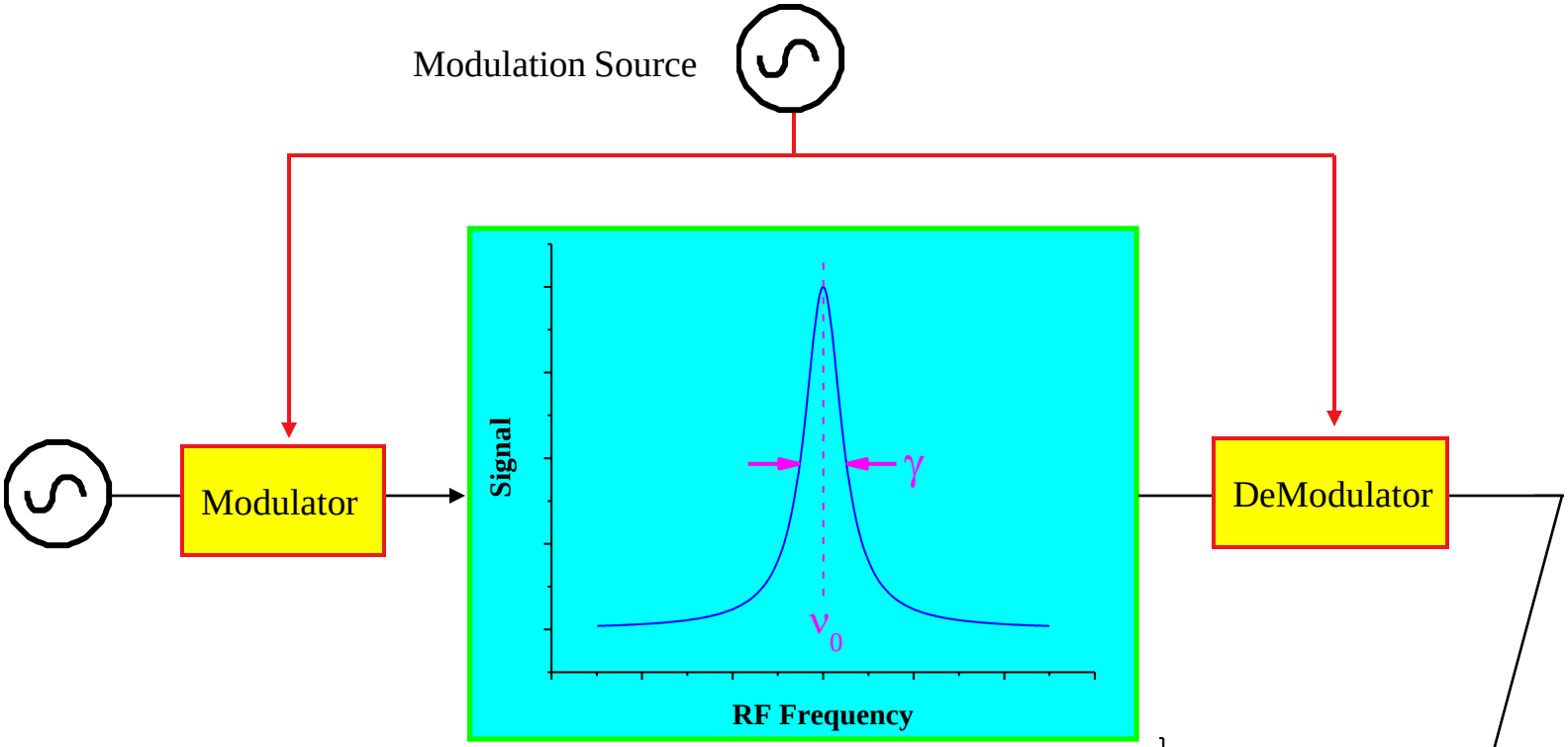
Control Loop periodically corrects LO frequency to atomic resonance.

LO output thus embodies stability of atomic resonance.

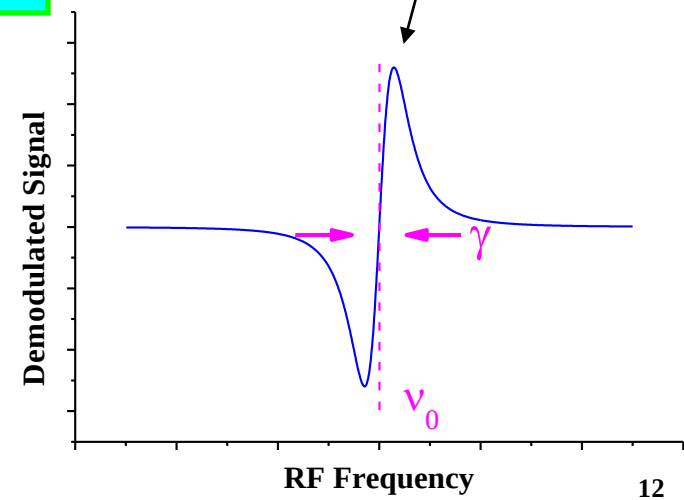
Clock performance is determined by accuracy and stability of the physics package, not by the properties of the LO.

Atomic properties are stable but perturbations may not be…

Physics Package



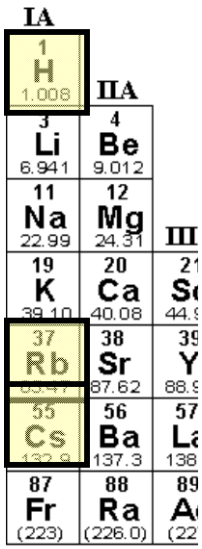
$Q = \nu_0/\gamma$



"Physics Package is a very narrow (high-Q) passband filter"

Typically $Q>10^7$

Ground State Physics

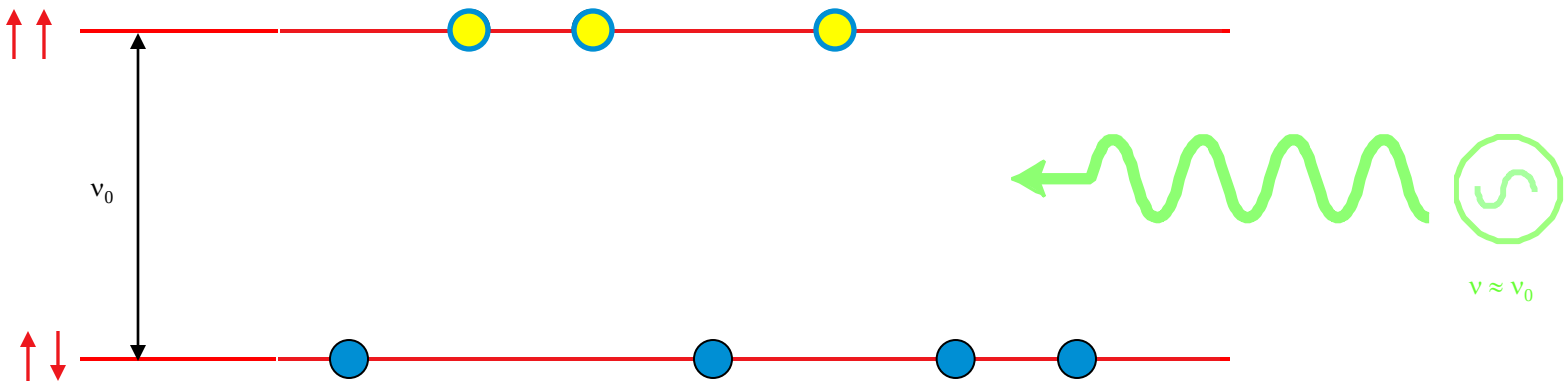


Step 1: Choose an Atom with two (and only two) ground states

Step 2: State Selection

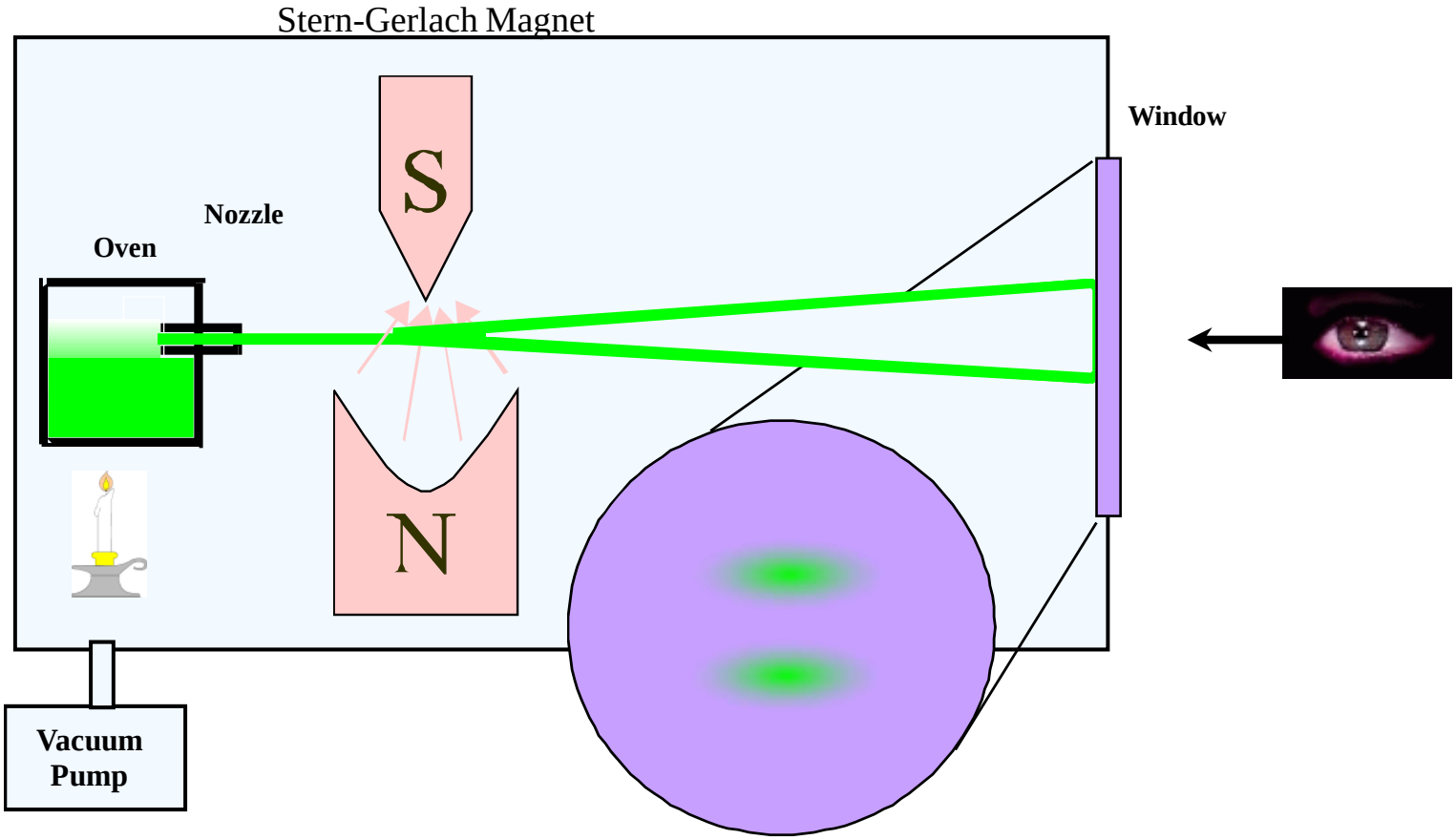
Step 3: Resonant Excitation

Step 4: Detection

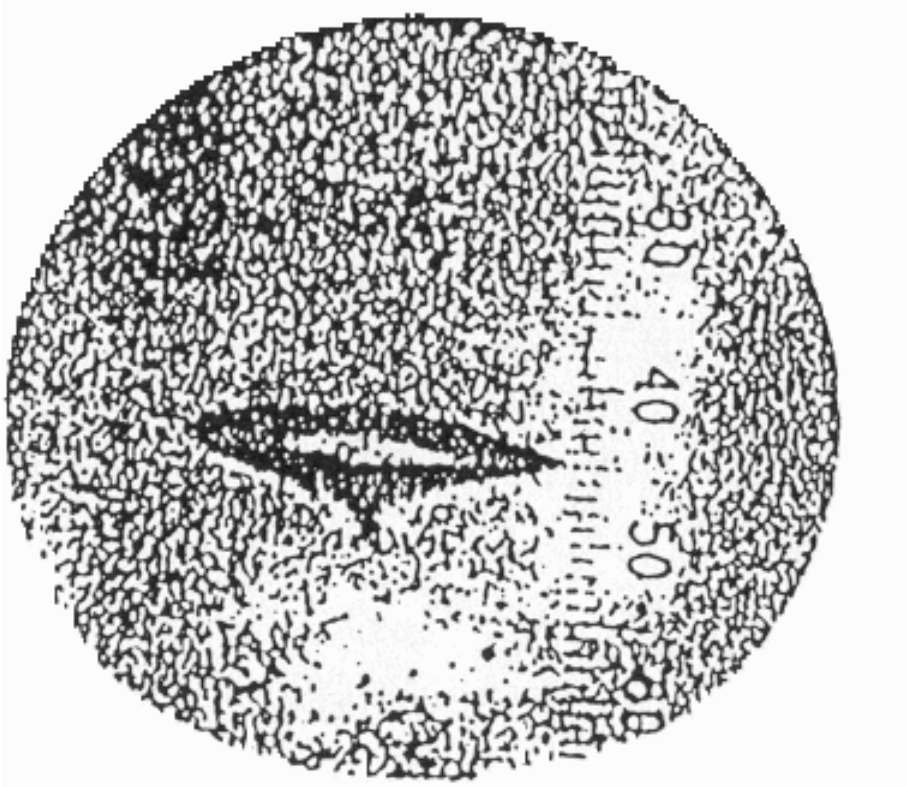


Cesium Beam Frequency Standard

Stern-Gerlach Experiment - 1922



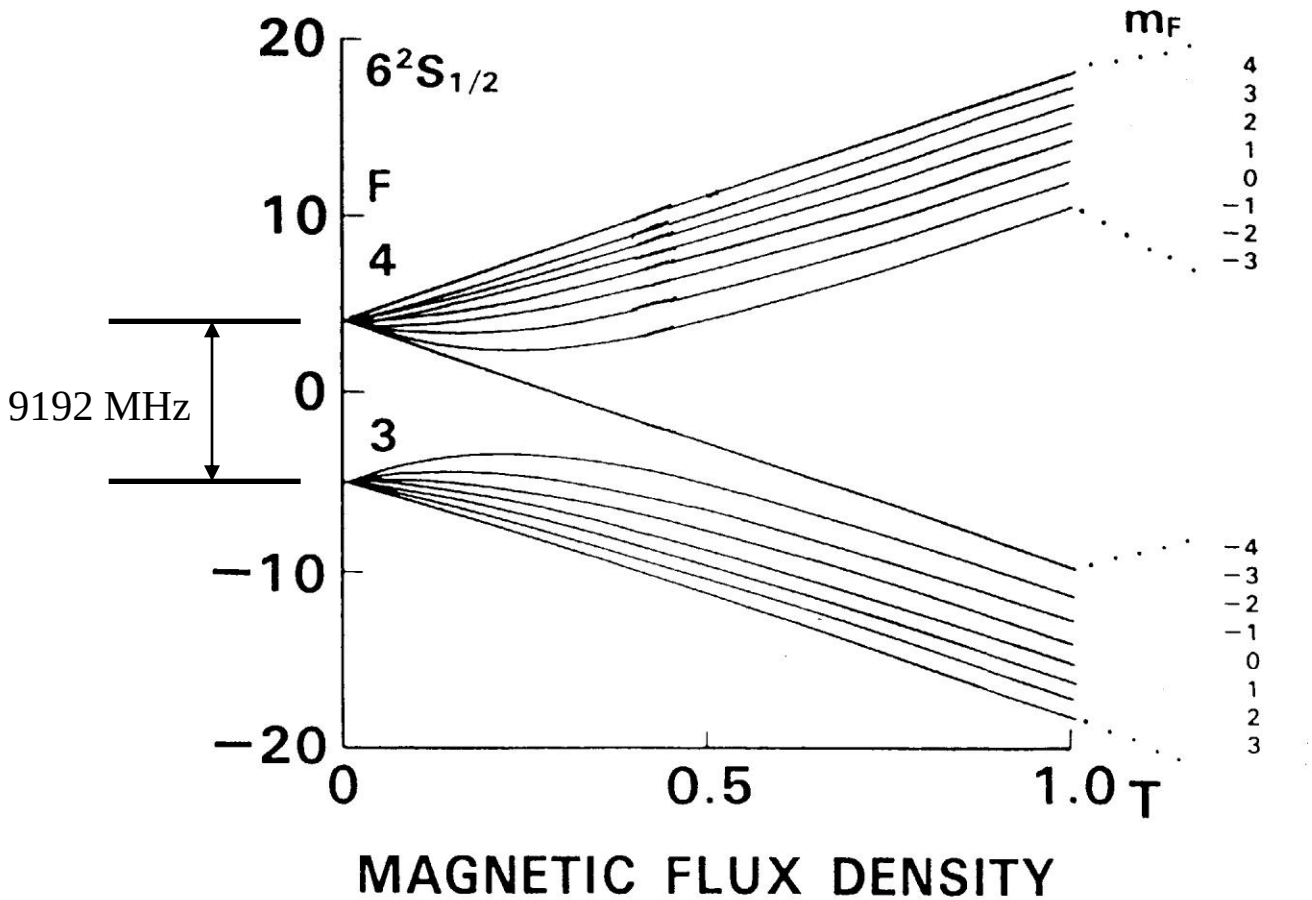
Nobel Prize 1943 – Otto Stern



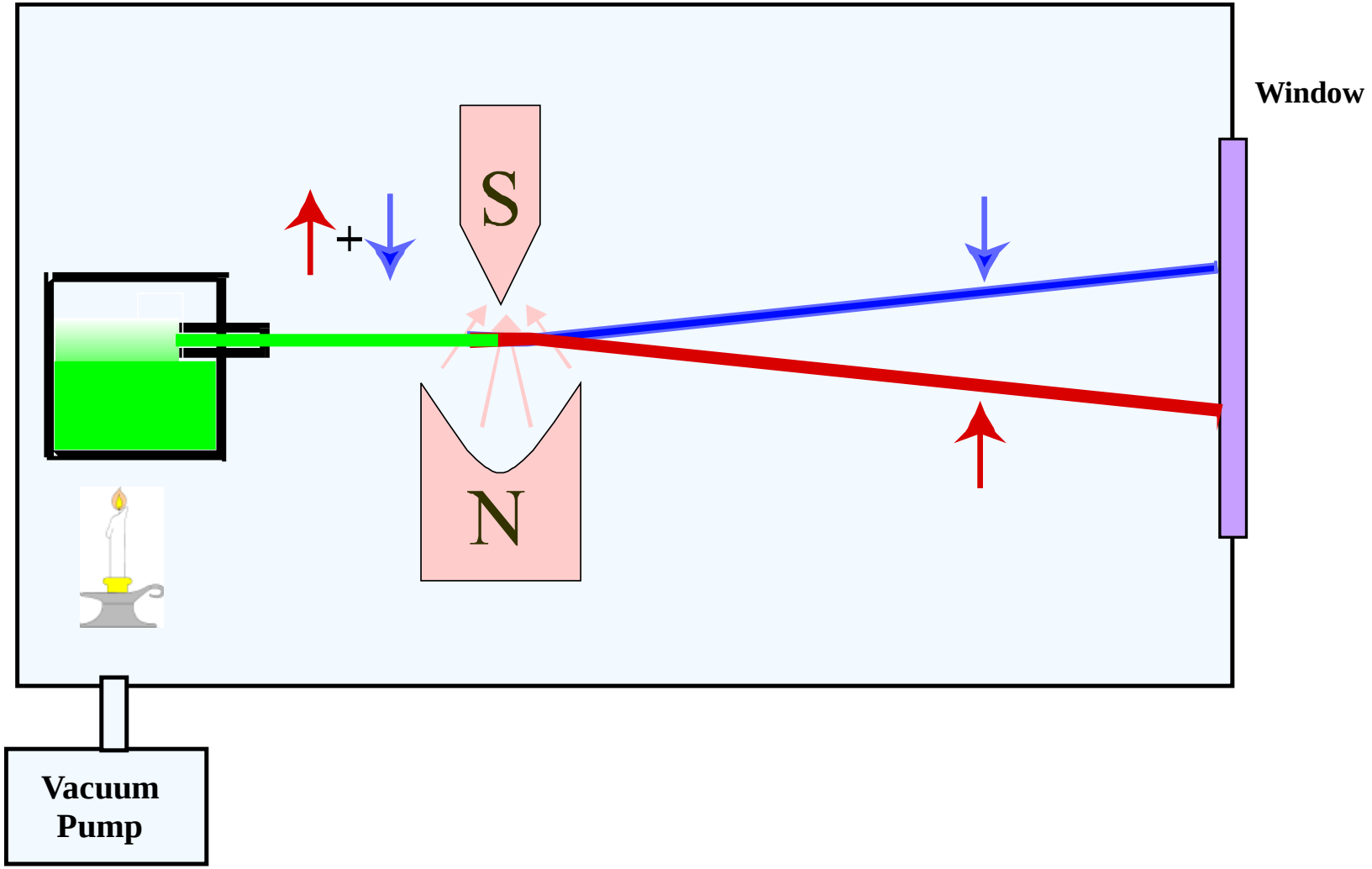
"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

Ground State Physics

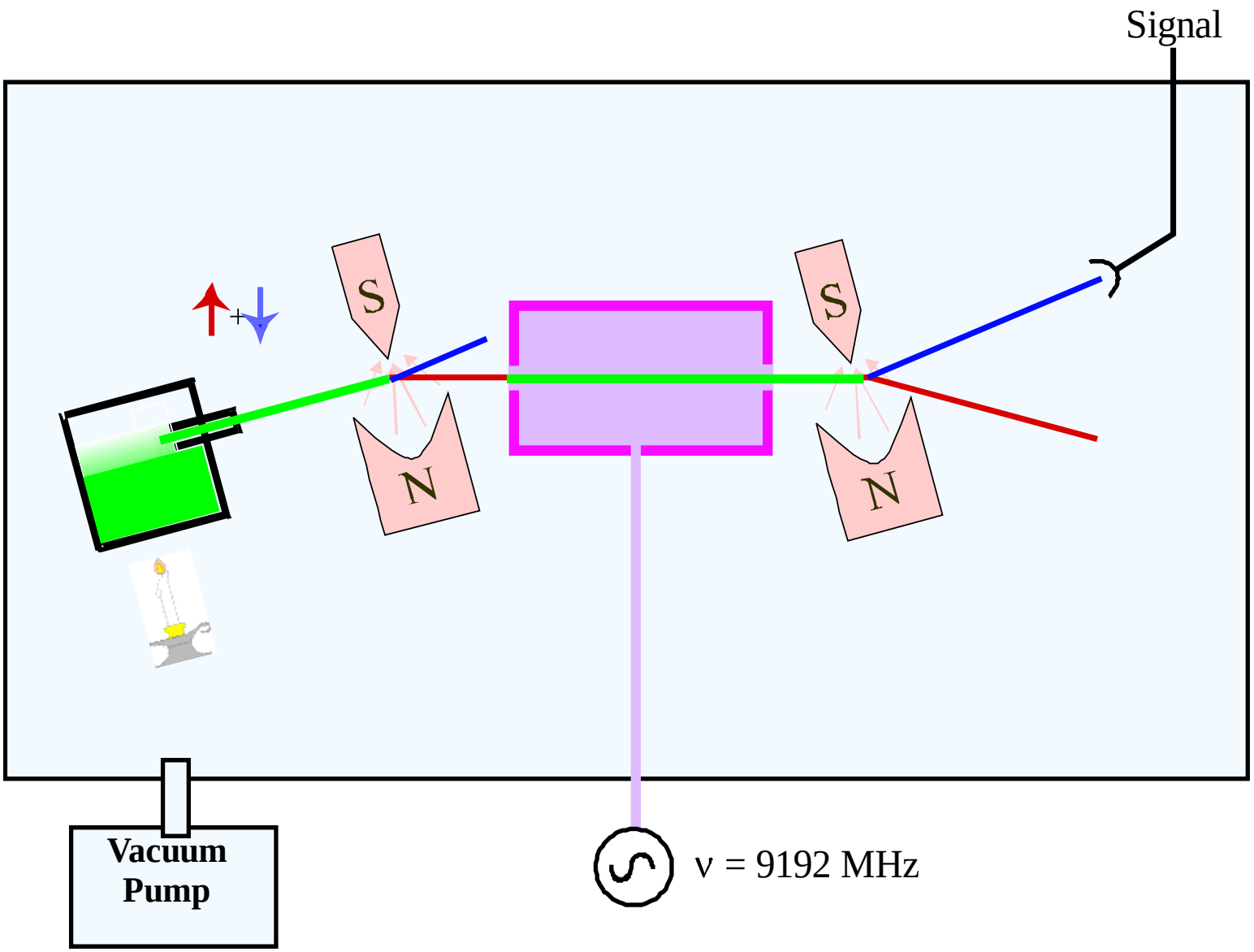
Energy levels in a magnetic field: The Zeeman Effect



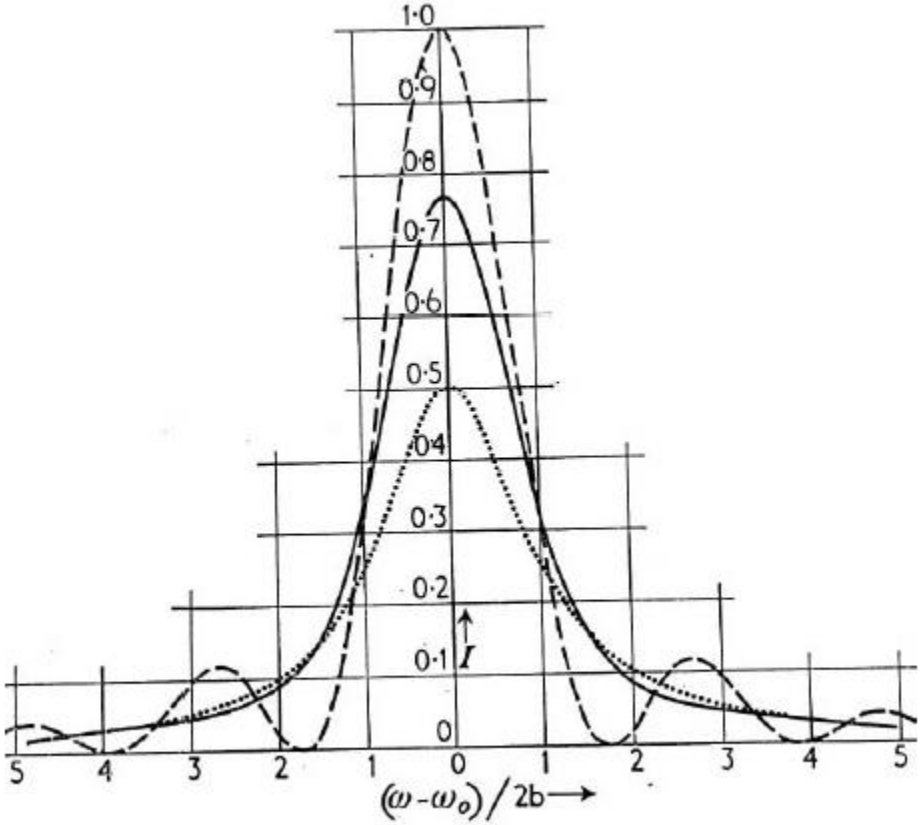
Stern-Gerlach Again



Molecular Resonance Spectroscopy



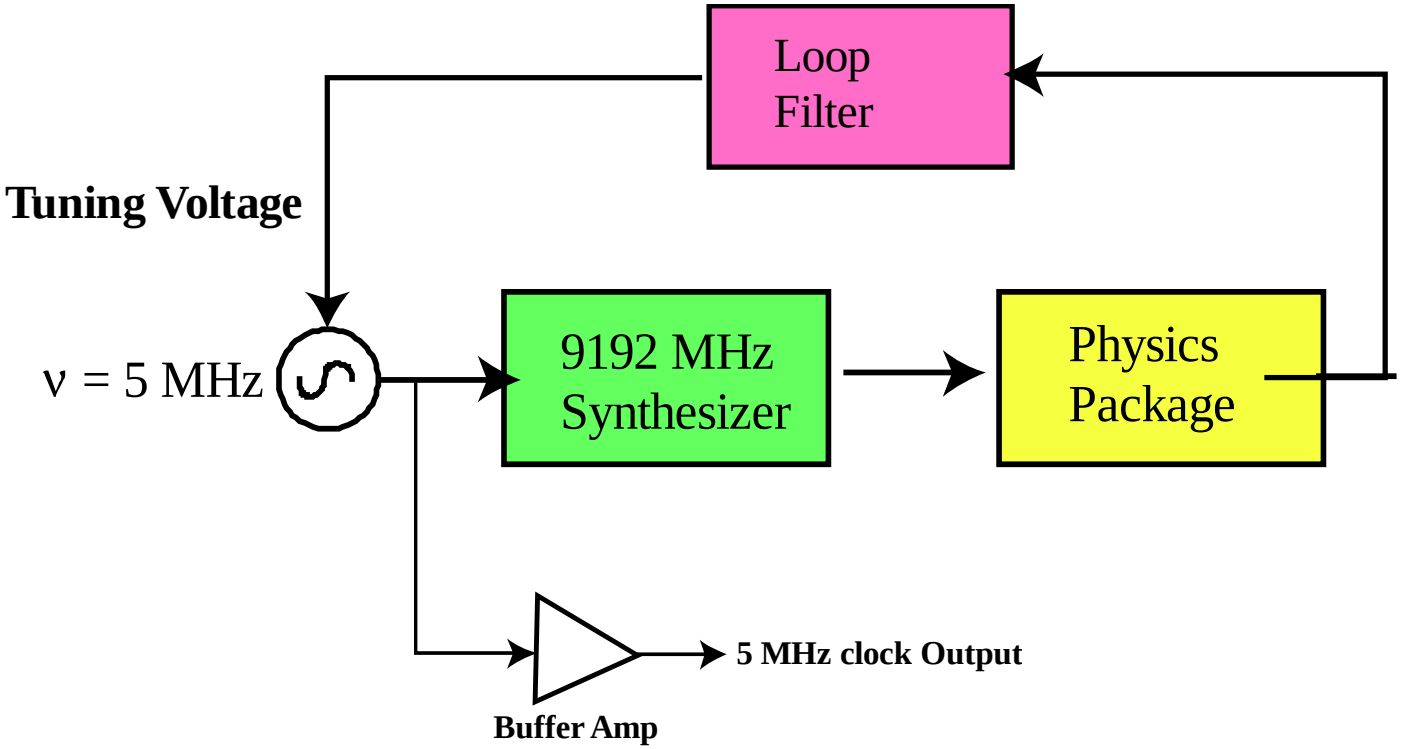
Nobel Prize 1944 – I.I. Rabi



"for his resonance method for recording the magnetic properties of atomic nuclei"

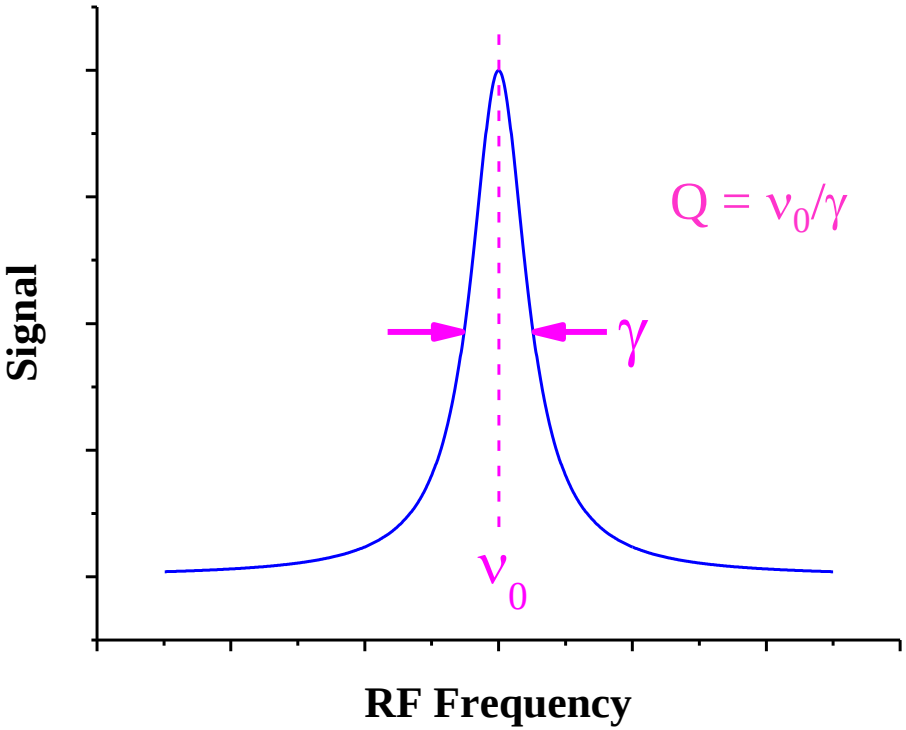
Invention of the Atomic Clock

Problem –Measurements limited by Quartz Oscillator



1944 – I.I. Rabi: "Just close the loop"

Atomic Clock Stability



Remember Equation 1:

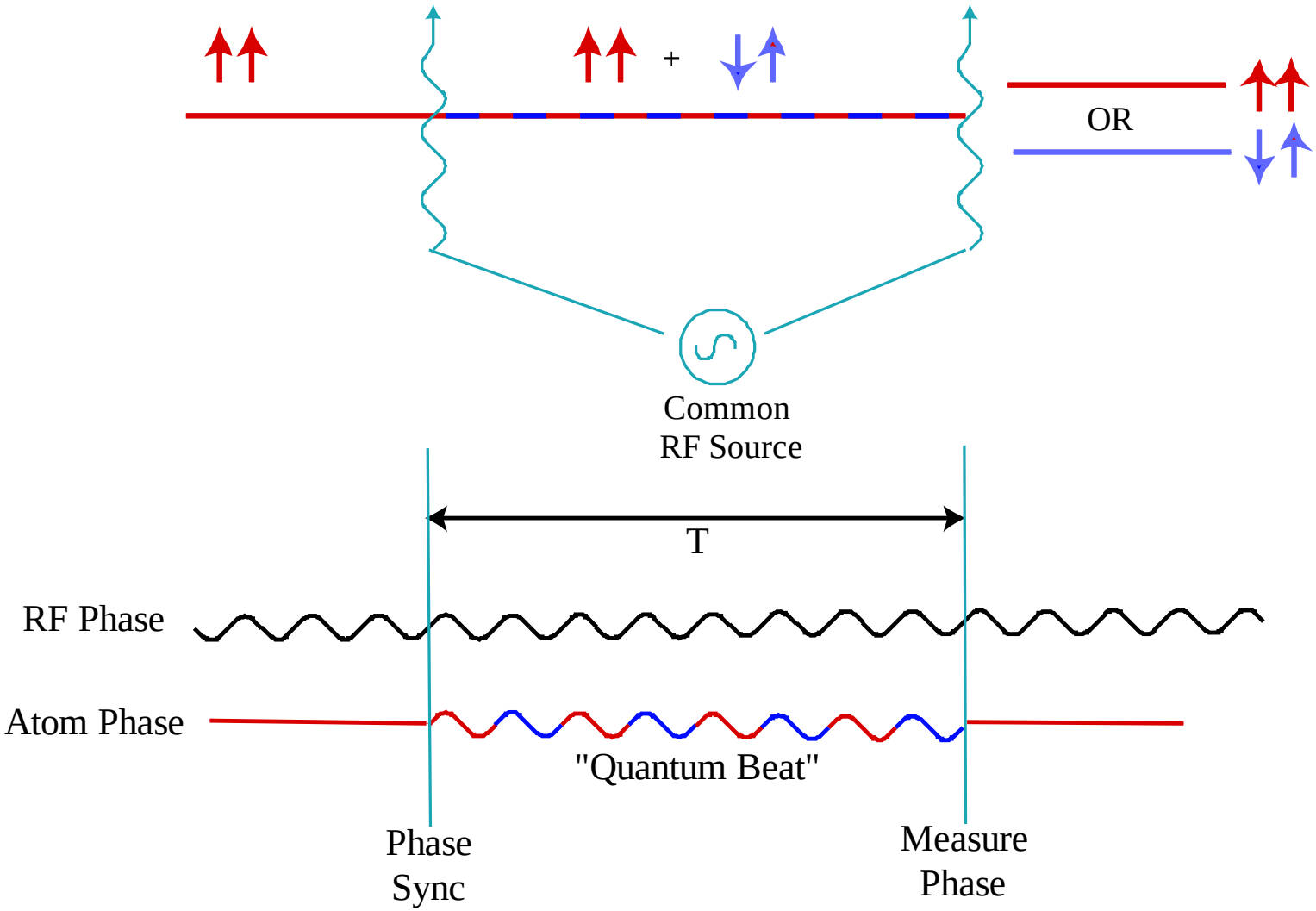
$$\sigma(\tau = 1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$

- S/N is limited by atomic beam flux
- ν_0 is resonance frequency – choice of atom
- γ is linewidth – limited by Fourier transform of measurement time, γT = constant

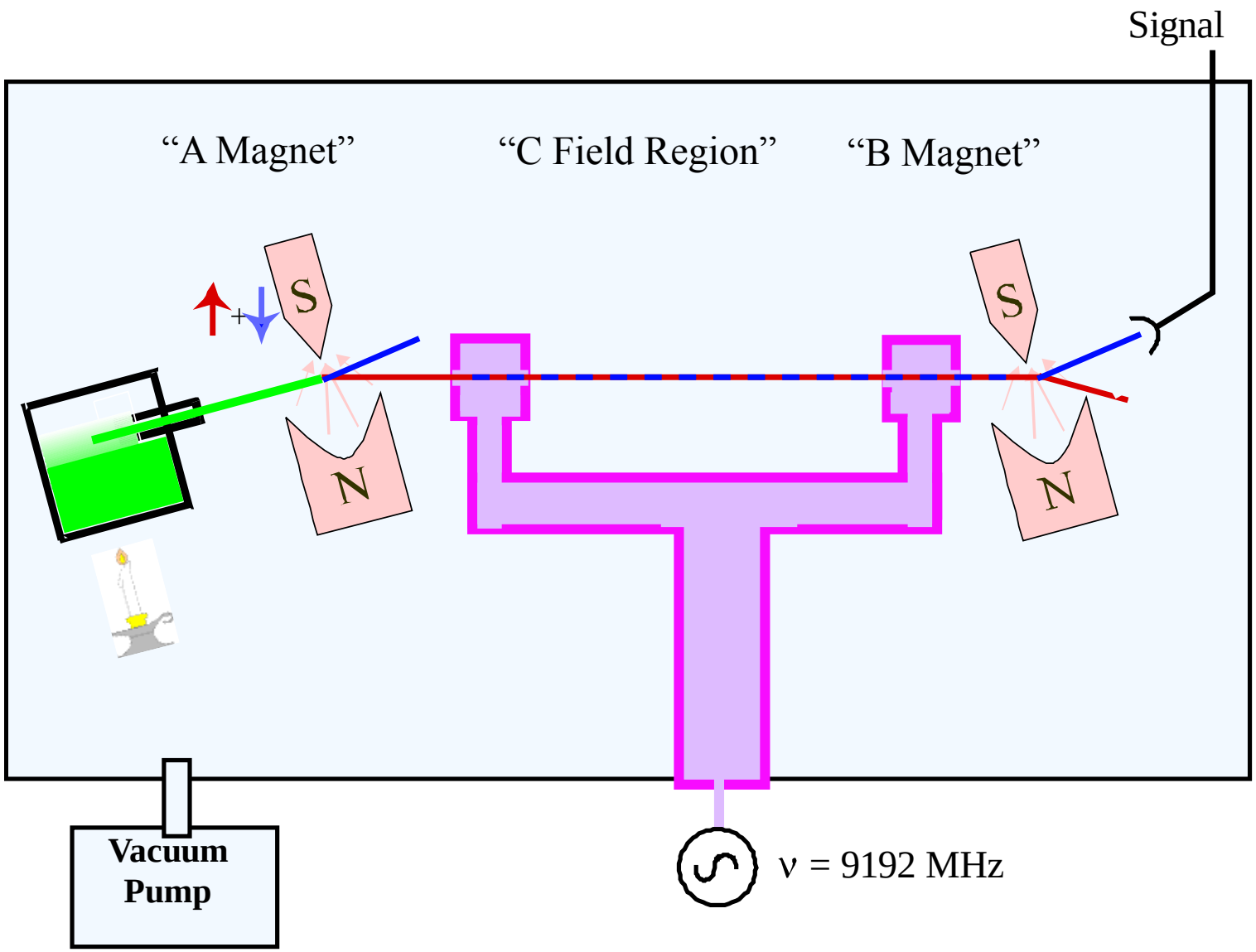
  In an atomic beam, interaction time (and thereby γ) is limited by time-of-flight of atoms through microwave field.

  It's very difficult to construct a uniform microwave field longer than a wavelength.

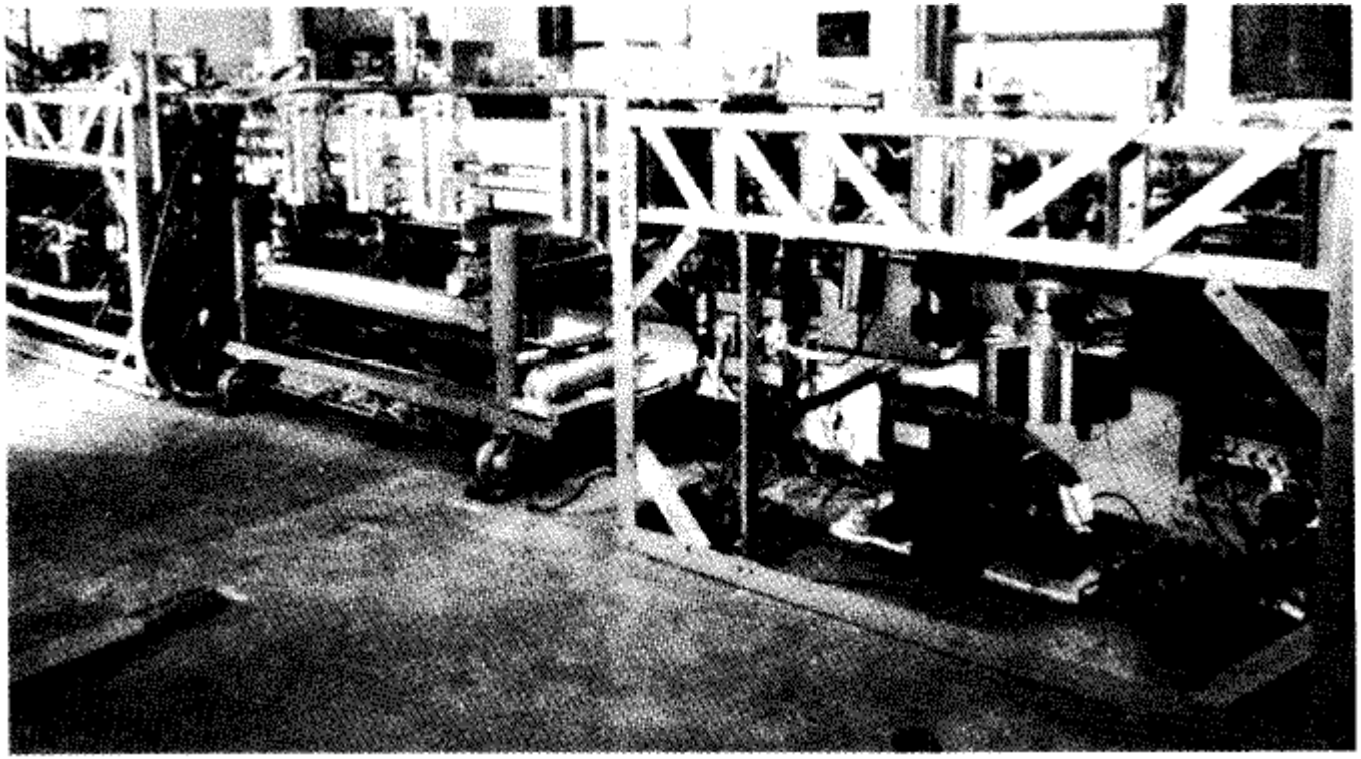
Ramsey: Separated Oscillatory Fields



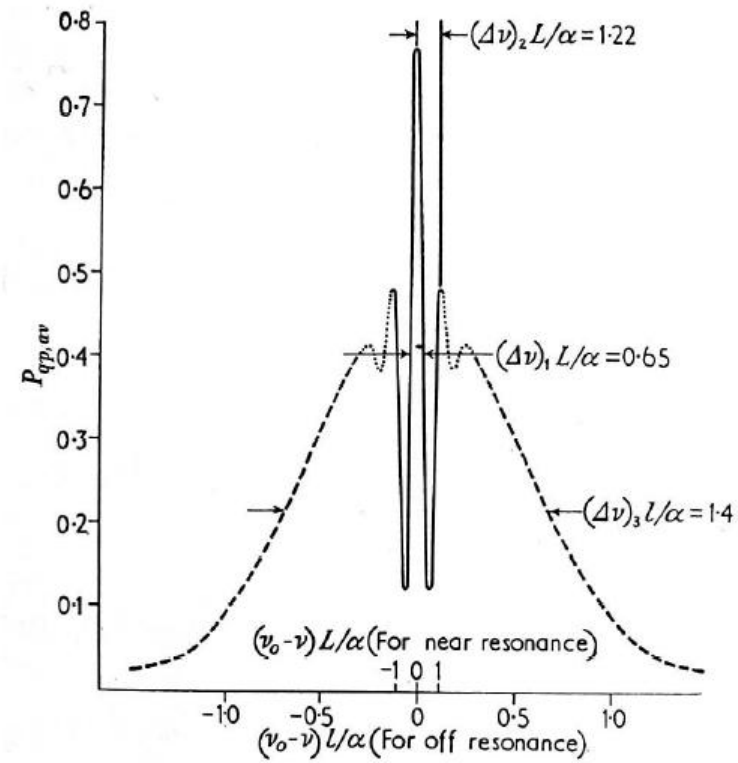
Ramsey: Separated Oscillatory Fields



Ramsey's Lab - 1949



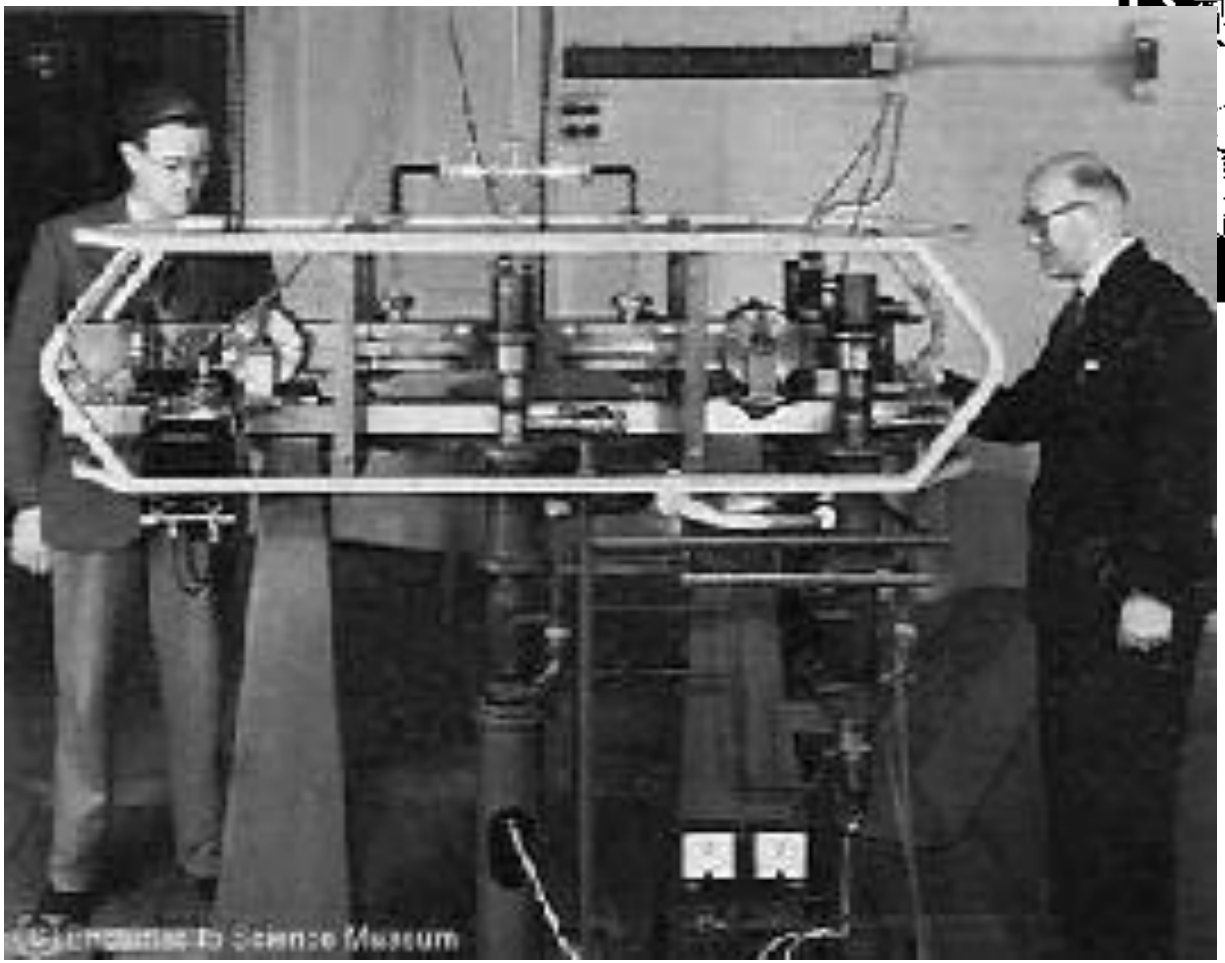
Nobel Prize 1989 – Norman Ramsey

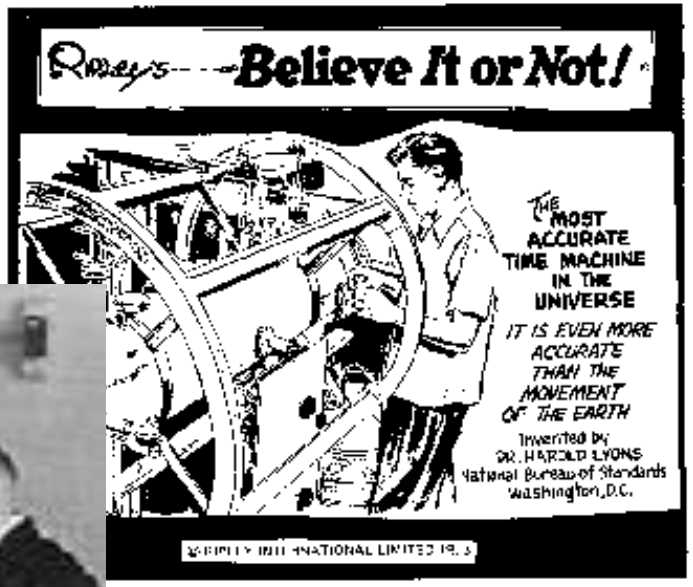


"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"

1955 NPL Cesium Clock

Essen & Perry 1953





Definition of Time

- Originally 1/86400 of the mean solar day
- 1967 CGPM - ***Conférence Générale des Poids et Mesures*** :

  "The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom."

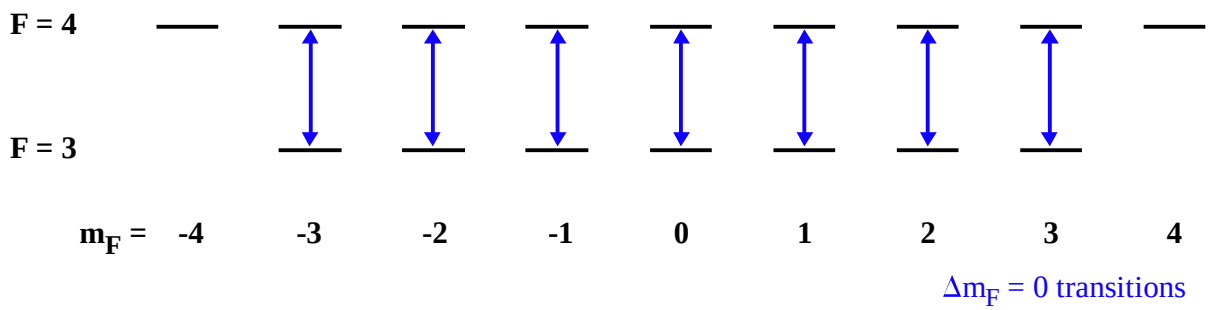
- 1997 CIPM - ***Comité International des Poids et Mesures***

"This definition refers to a cesium atom at rest at a temperature of 0 K."

CFS Biases

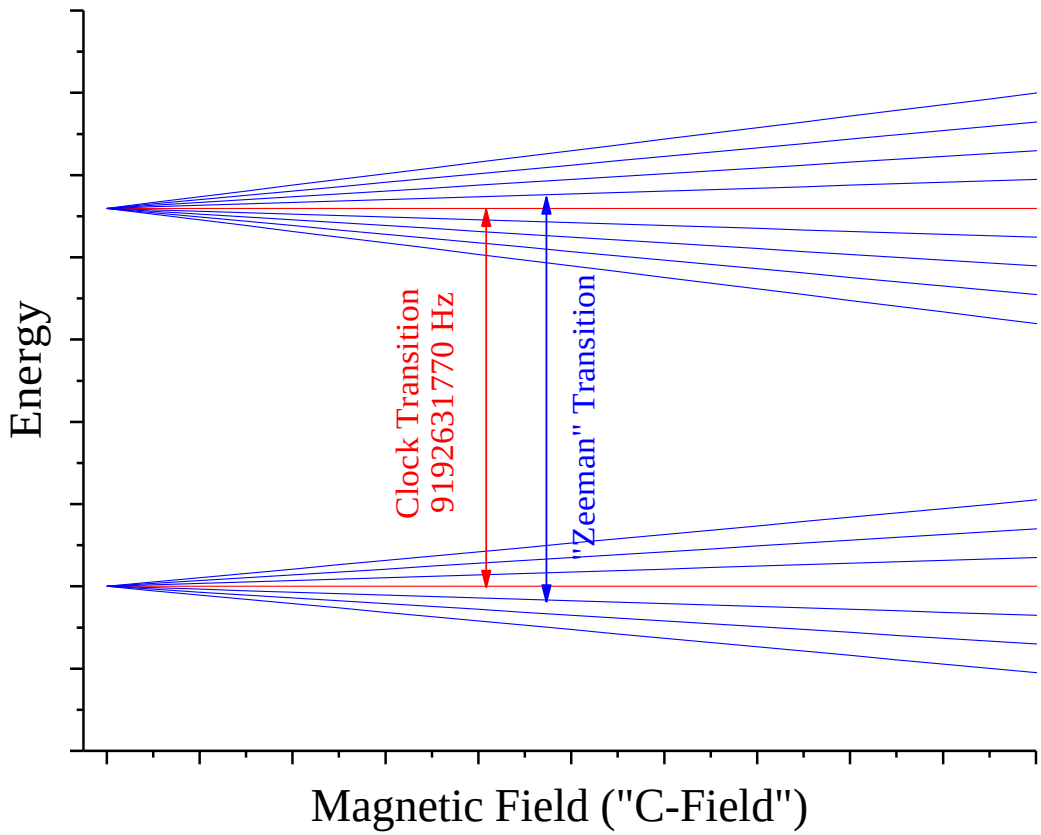
- Atom is not in “zero field”
  - Magnetic fields (Zeeman effect)
  - Electric fields (Stark effect)
  - Radiation (AC-Stark effect or “light shift”), including blackbody
  - Gravity
- Atom is not “at rest”
  - First-order Doppler shift
  - Second-order (relativistic) Doppler shift
- Spectral Perturbations
  - Rabi pulling
  - Ramsey pulling
- Mechanical Effects
  - End-to-end phase shift
  - Cavity pulling
  - Majorana transitions
- Electronic Effects
  - Microwave spectrum
  - Servo biases

Cesium Hyperfine levels



Selection Rule:

$\Delta m_F = 0, \pm 1$



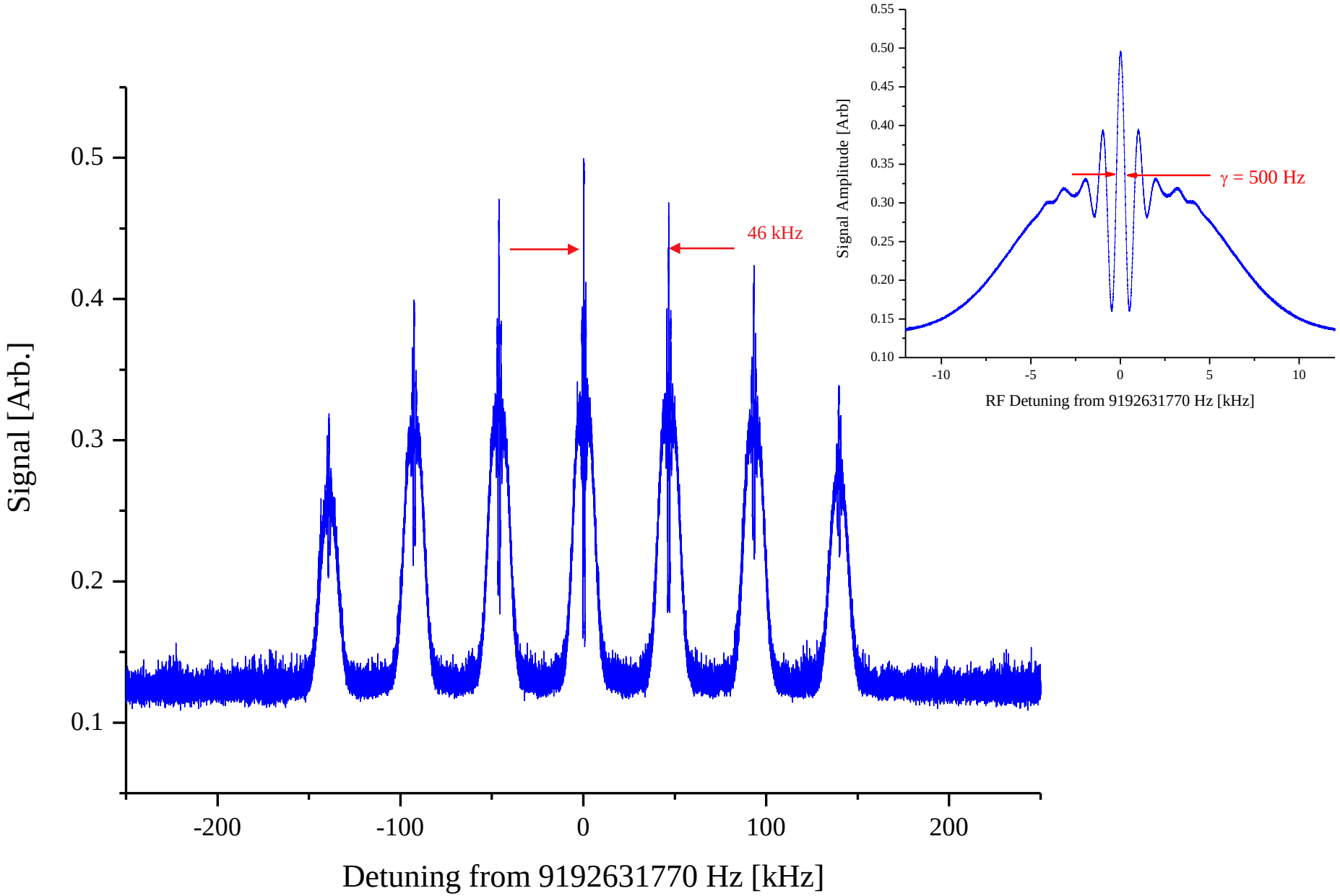
Clock Transition

≈427.45 Hz/Gauss^2

Zeeman Transition

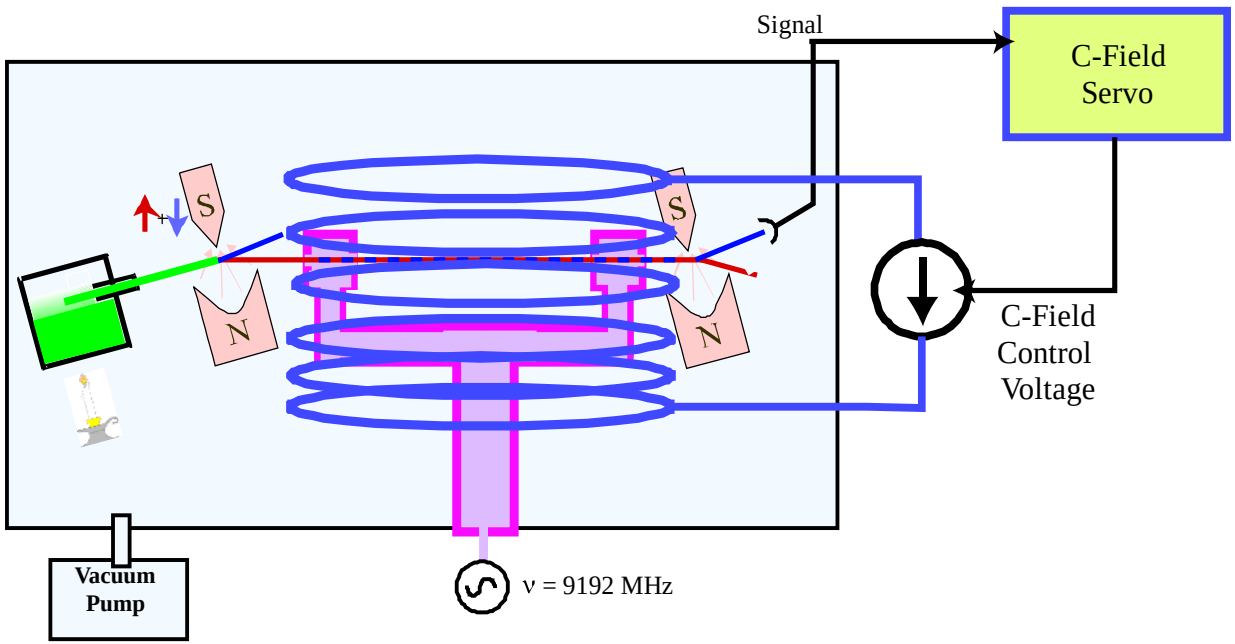
≈700 kHz/Gauss

Zeeman Spectrum



Zeeman Servo

- Interrogate first linearly shifted Zeeman resonance to measure C-Field
- 10^{-11} measurement of Zeeman frequency determines second-order clock shift to 10^{-15}



State-of-the-art Cesium Clocks

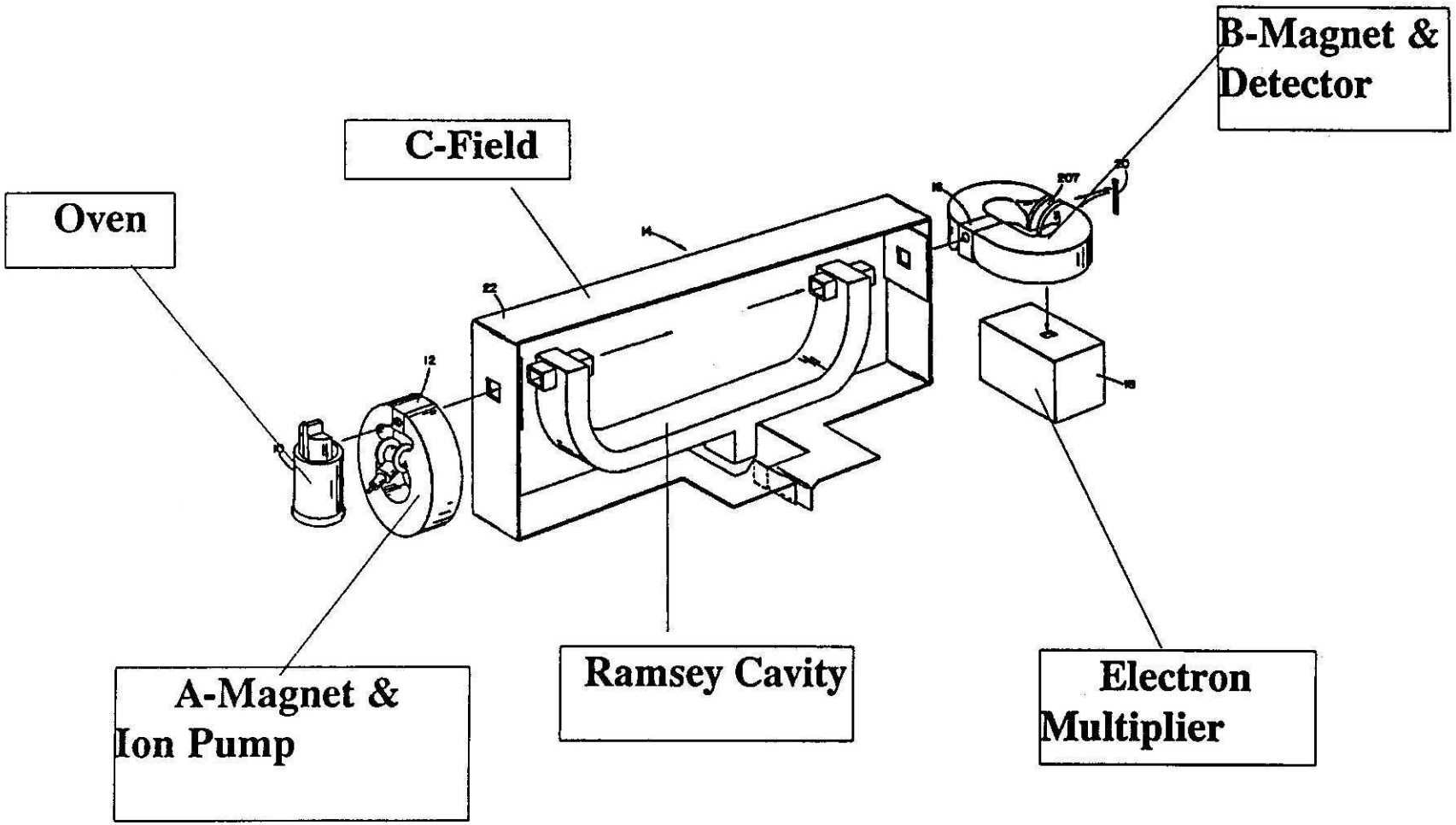
PTB CS1 (1965 - present)

NBS-6 circa 1975

Cesium Beam Tube

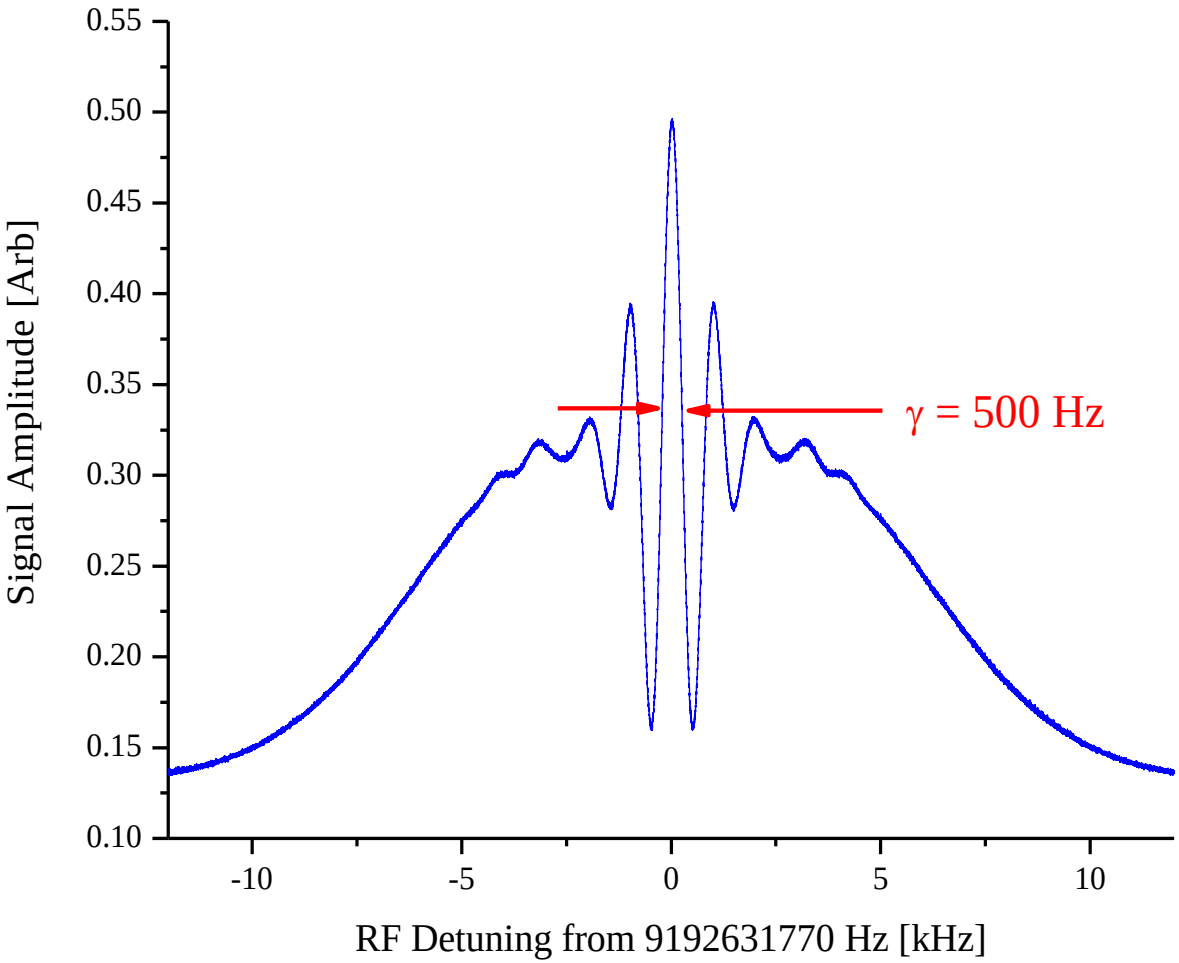
Symmetricom-7505

Cesium Beam Tube Construction



Source: U.S. Patent # 3,967,115

CBT Spectrum



$$Q = 2\text{x}10^7$$

$$(S/N)_{1\text{Hz}} = 3000$$

$$\sigma(1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$

$$\approx 2 \times 10^{-11}$$

Linewidth (and Q) limited by time-of-flight of atoms through microwave region

Signal/Noise limited by atomic beam flux: $Noise \propto \sqrt{Signal}$

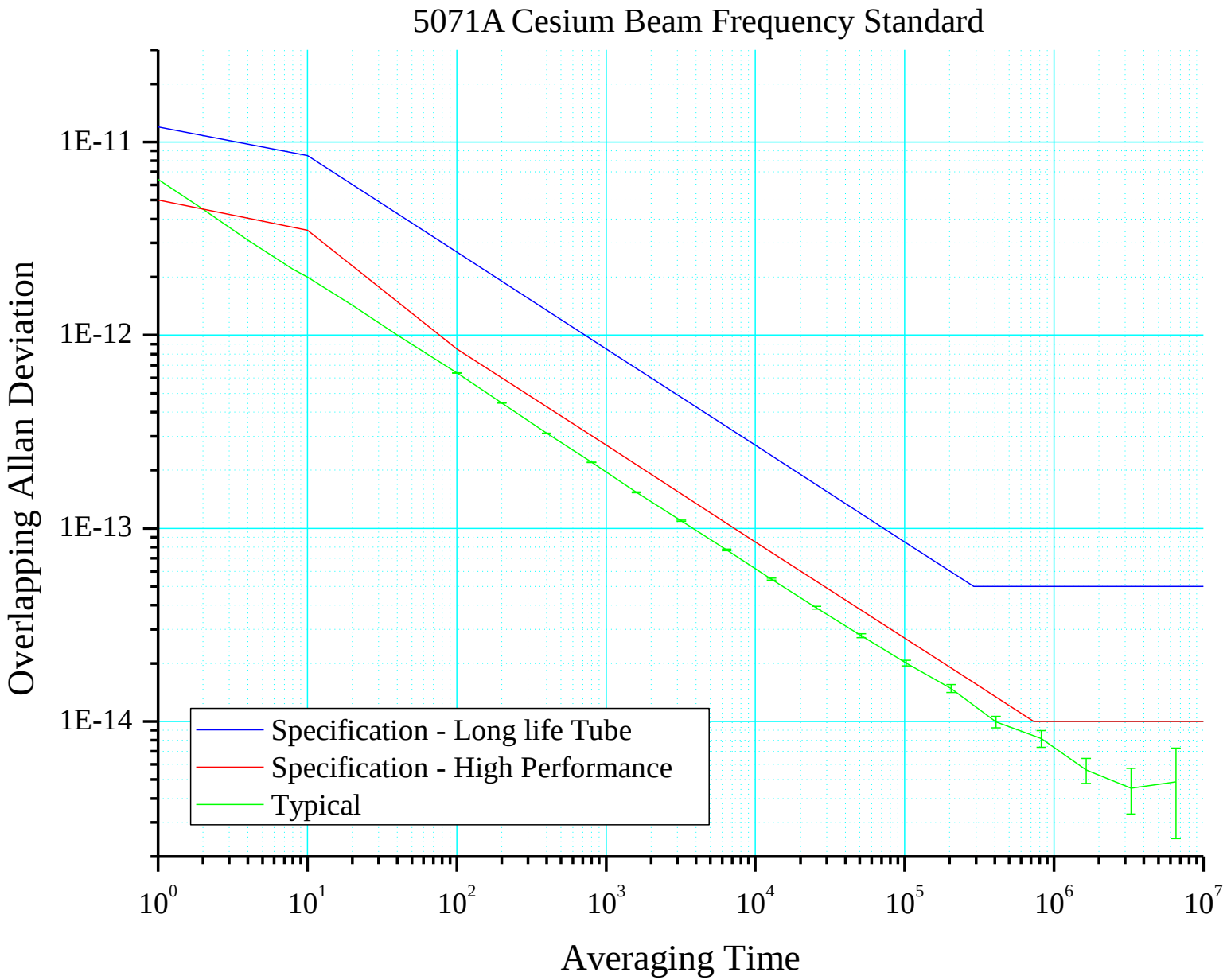
CFS Instruments

Laboratory/Timekeeping

Telecom

Space/GPS

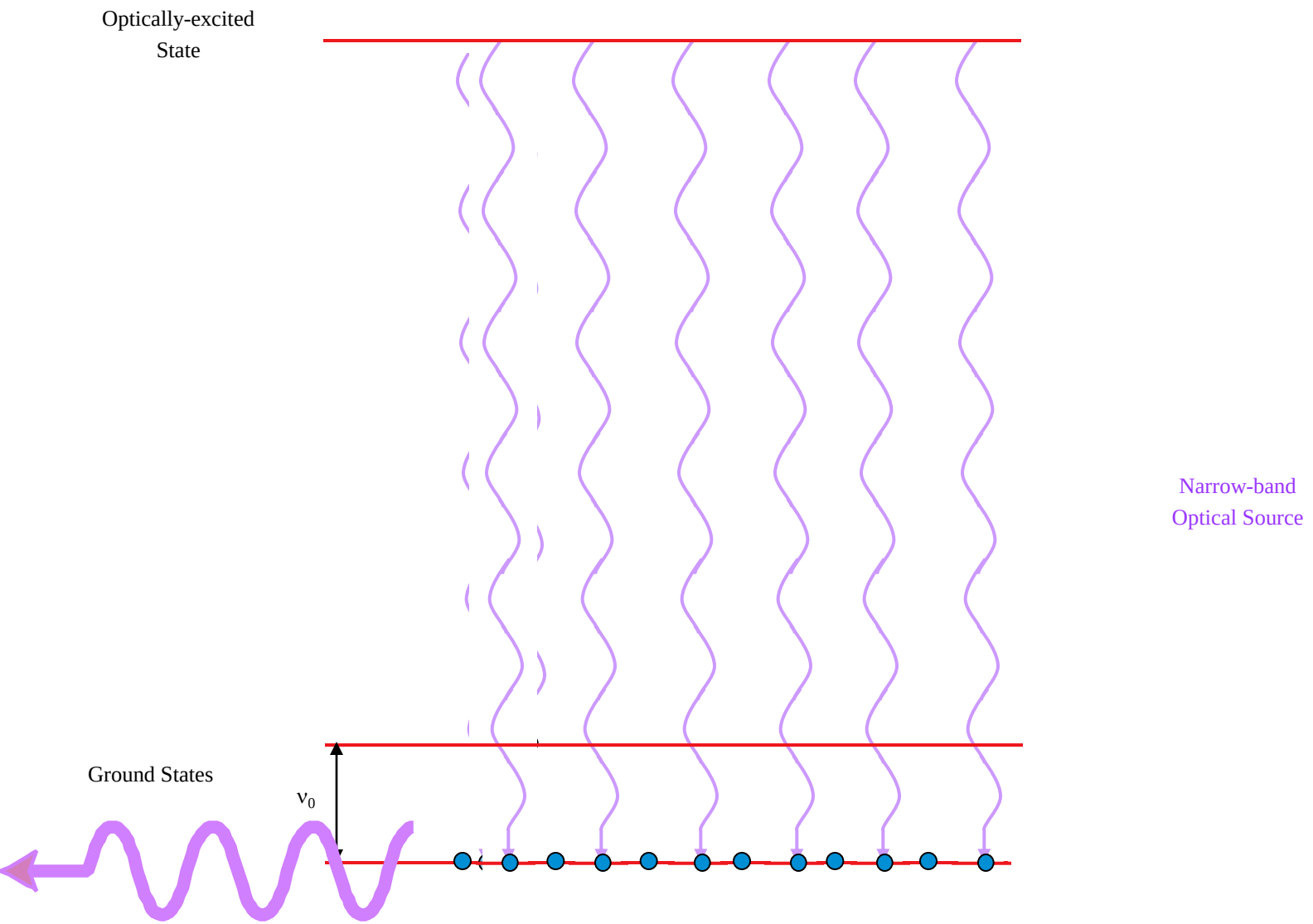
Stability


5071A Cesium Beam Frequency Standard
Overlapping Allan Deviation
1E-11
1E-12
1E-13
1E-14
Specification - Long life Tube
Specification - High Performance
Typical
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Averaging Time

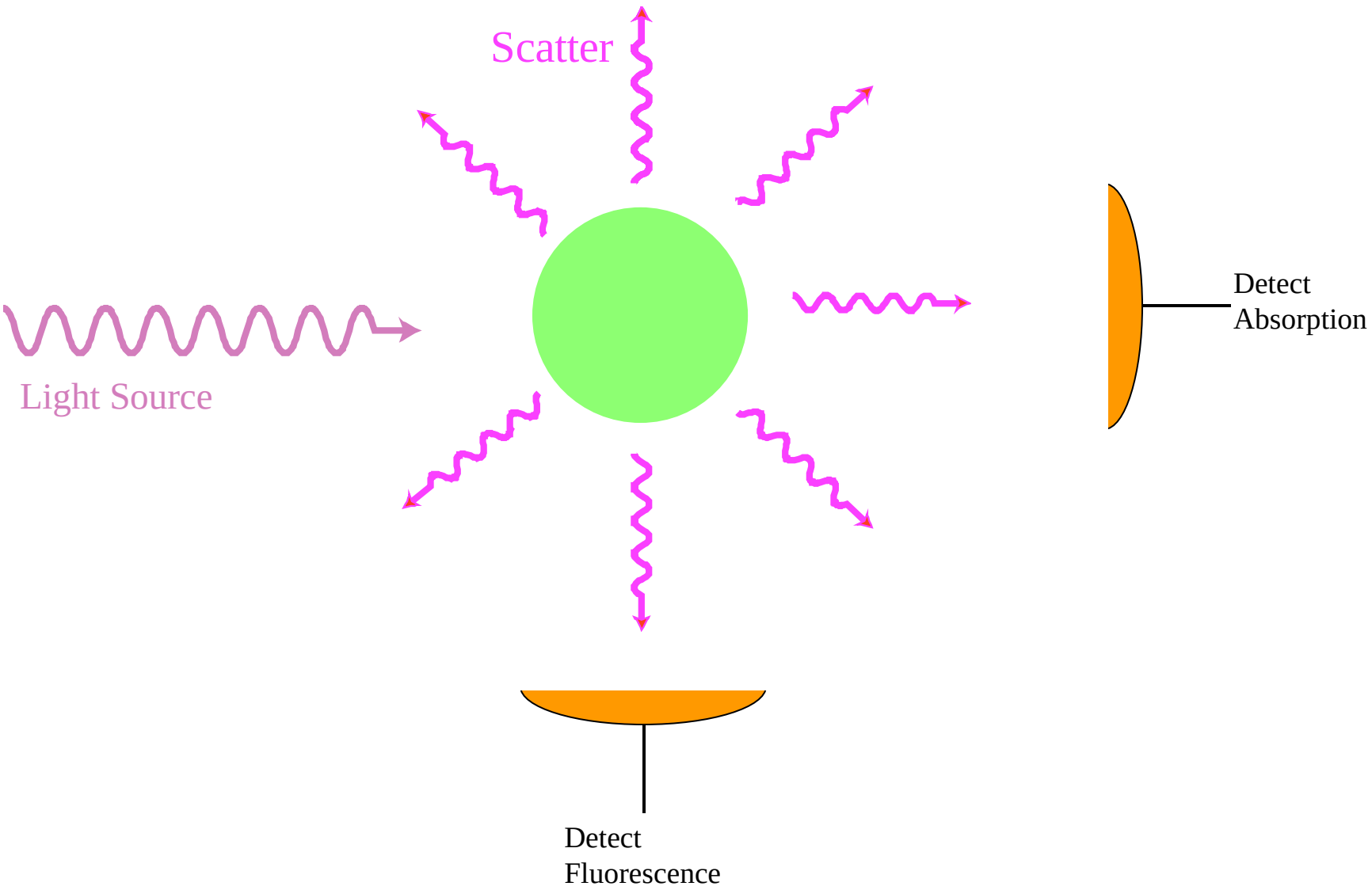
The Ubiquitous Rubidium Oscillator

Low-cost stability

State Selection by Optical Pumping



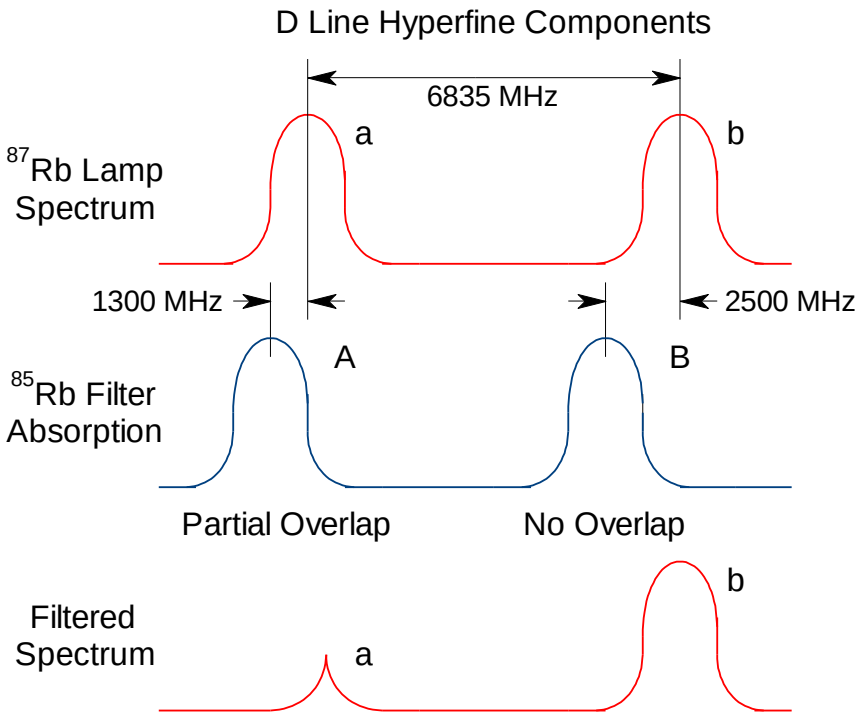
State Detection by Optical Scattering



Hyperfine Filtration

Carver & Alley 1958

"Fortuitous" overlap between the optical absorption lines of the two naturally-occurring isotopes, ^{85}Rb and ^{87}Rb.

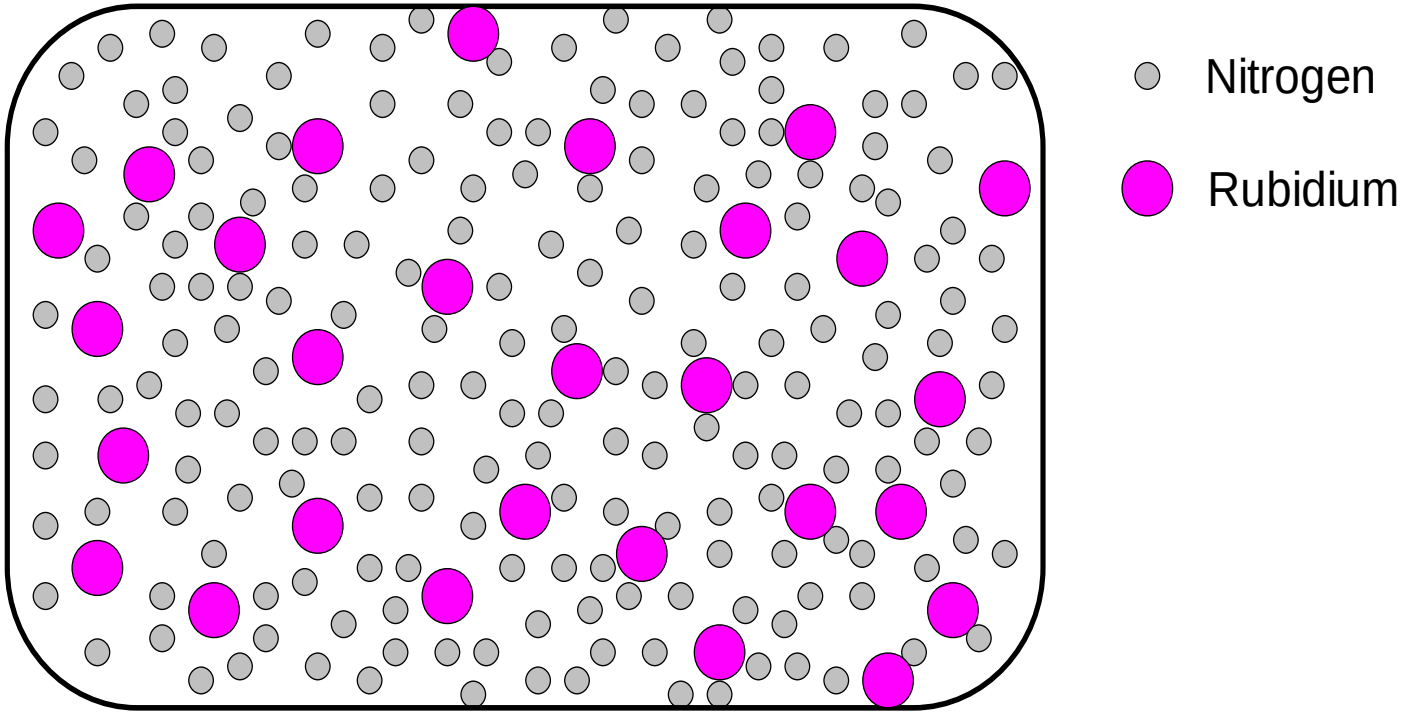


Isotopic Filtering of Rubidium 87 D Lines

Courtesy of WJ Riley *2002 PTTI Tutorial*

Gas Cell Confinement

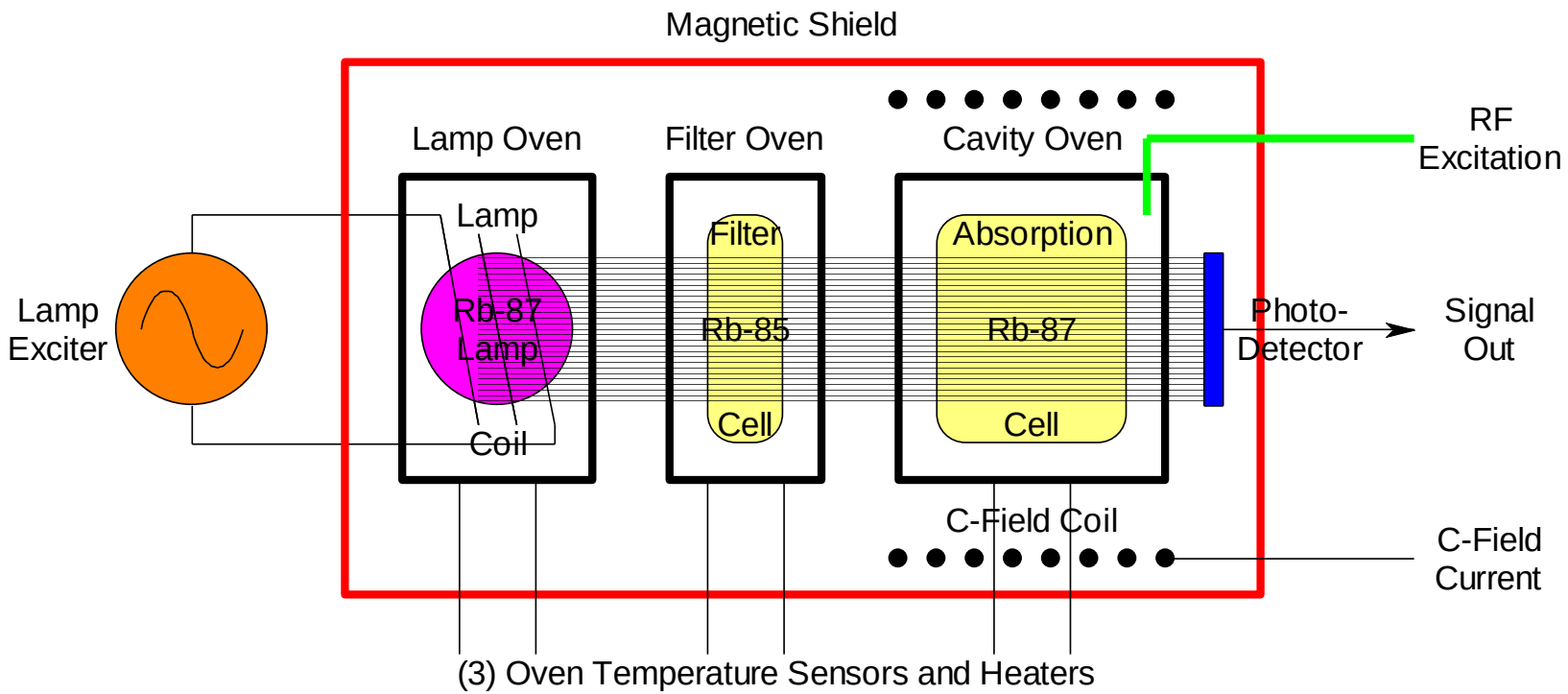
Dicke 1953



- RbO atomic resonance linewidth, γ, is limited by decoherence of population inversion due to collisions with walls and other Rb atoms
- Nitrogen "buffer gas" atoms "immobilize" Rb with minimal decoherence
  - Reduces Rb-Rb and Rb-wall collisions
  - Eliminates first-order Doppler shift

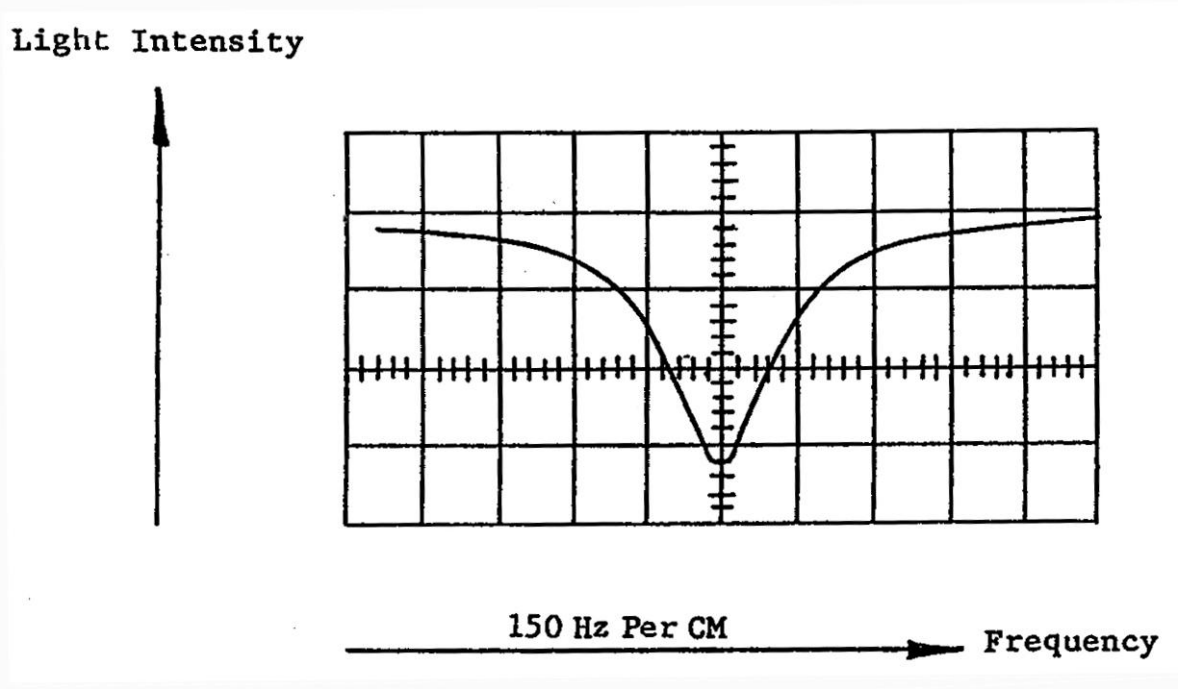
Symmetricom

Rb Gas Cell Physics Package



Courtesy of WJ Riley 2002 PTTI Tutorial

RF Spectrum



$$Q = 2\text{x}10^7$$

$$(S/N)_{1\text{Hz}} = 3000$$

$$\sigma(1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$

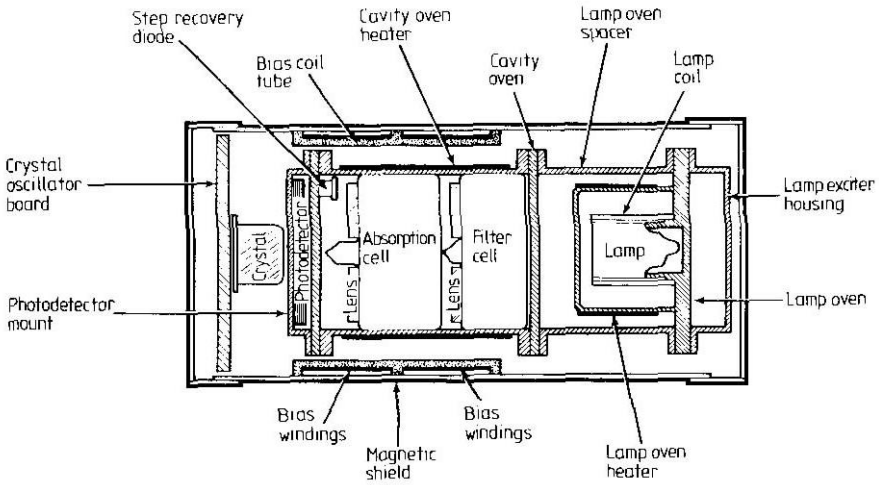
$$\approx 2 \times 10^{-11}$$

Linewidth (and Q) limited by decoherence due to collisions between Rb and Rb, buffer gas, and cell walls

Signal/Noise limited by shot noise of background light: $Noise \propto \sqrt{Intensity}$

Factors which impact Performance

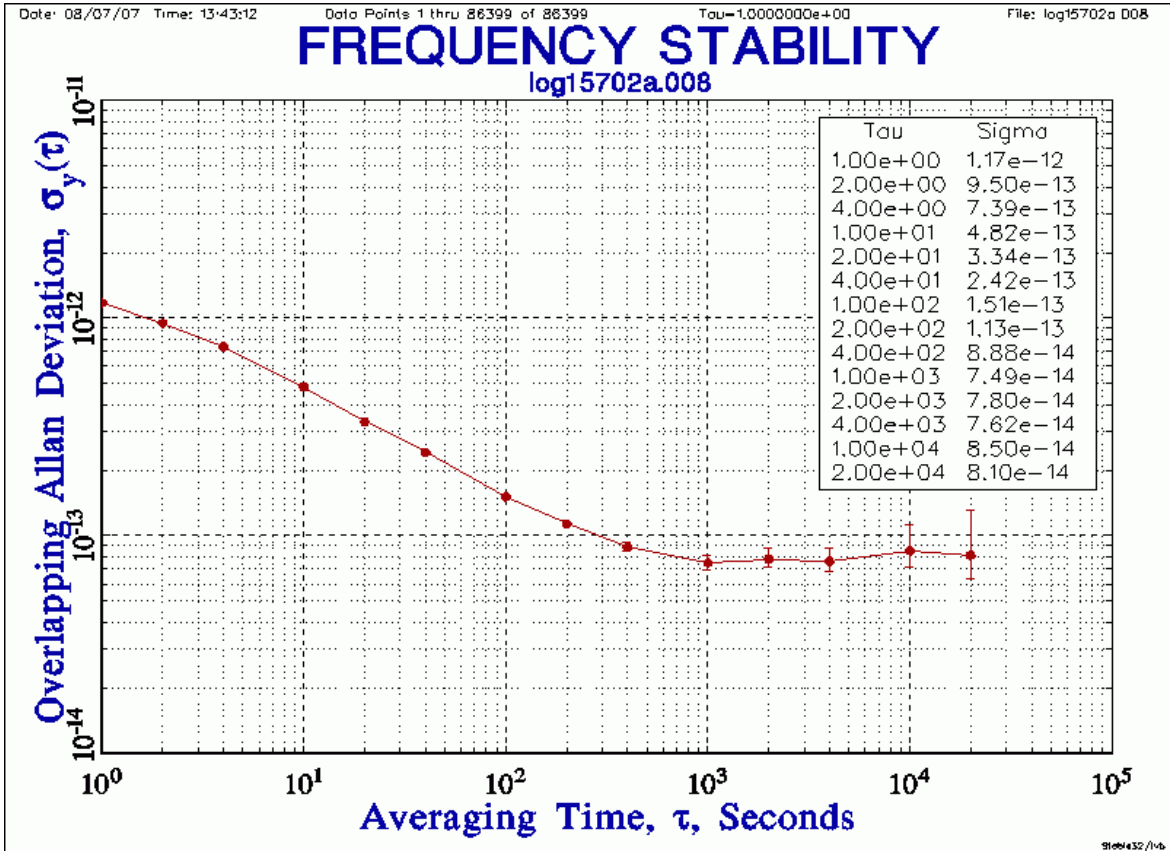
- Short-term stability
  - Optimize linewidth & S/N
  - Lamp output – gas mix, RF drive, temperature, etc.
  - Filter cell – gas mix, temperature
  - Resonance cell – Microwave phase stability, gas mix, cell temperature
- Medium-term stability
  - Thermal control circuits, thermal isolation
  - Gas mixtures to reduce temperature sensitivity
  - Ambient pressure effects (“oil-canning”)
  - Magnetic shielding
- Long-term stability (drift)
  - Stability of buffer gas mixture
  - Rubidium migration



EG&G RFS-10 Physics

Figure from J. Vanier and C. Audoin,
The Quantum Physics of Atomic Frequency Standards.

HP 5065A circa 1970

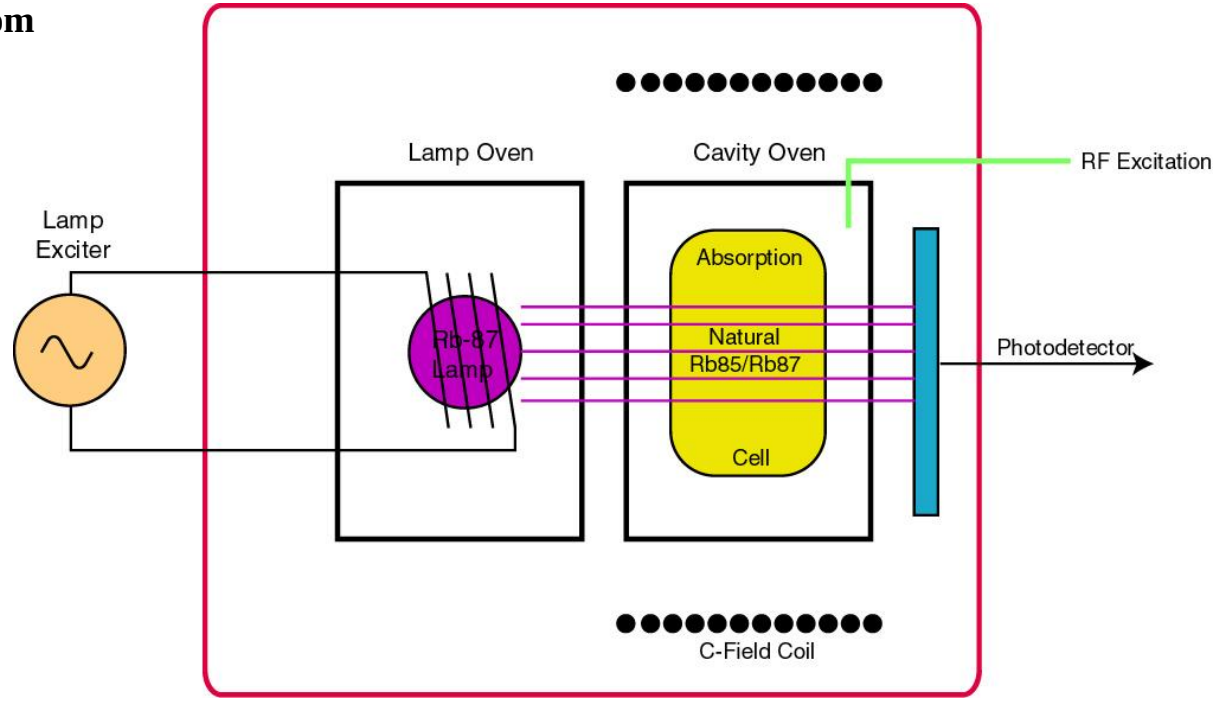


- **33 Watts, 37 lbs**
- **$\sigma_y(\tau) < 5 \times 10^{-12}\,\tau^{-1/2}$**
- **Drift < 2×10^{-11}/month**

"Typical" data courtesy of T. Van Baak (www.leapsecond.com)

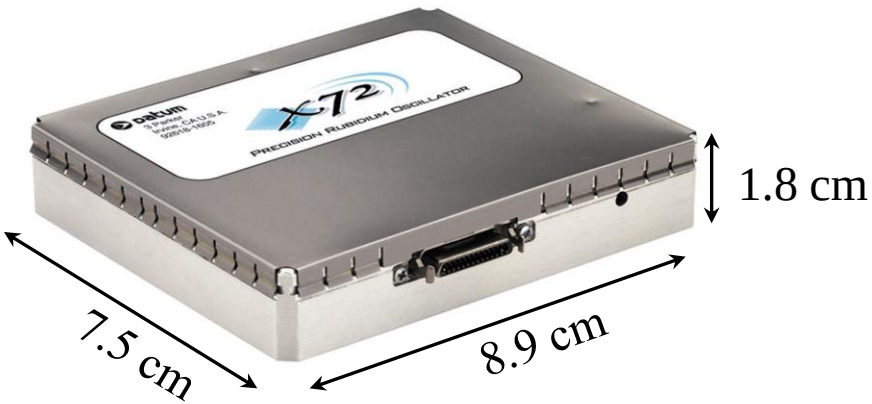
Integrated cell

E. Jechart, Efratom
early 1970s



- Isotopic filtering within resonance cell
- Eliminate filter cell oven/controller, pure Rb-85, etc.
- Smaller, lower power, lower cost
- Degraded STS, TempCo

Small modern Rb oscillators



Volume ≈ 125 cm^3

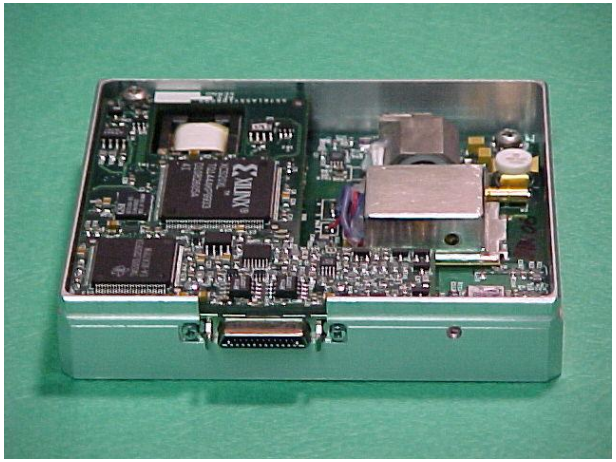
Power ≈ 8 W

Stability < $3x10^{-11}$ @ 1 second

Drift < $5x10^{-11}$/month

LPRO and X72 Rb Cells

- Small cell → small signal/Broad linewidth
- Microprocessor control
  - Digital microwave synthesis
  - Digital temperature compensation
  - Self-diagnostics



Rb Clocks

Stanford Research PRS10

Frequency Electronics
FE-5680A

Quartzlock E10

Temex SR100

PerkinElmer GPS RAFS

Symmetricom X72

Accubeat AR-70A

Images from WWW sites

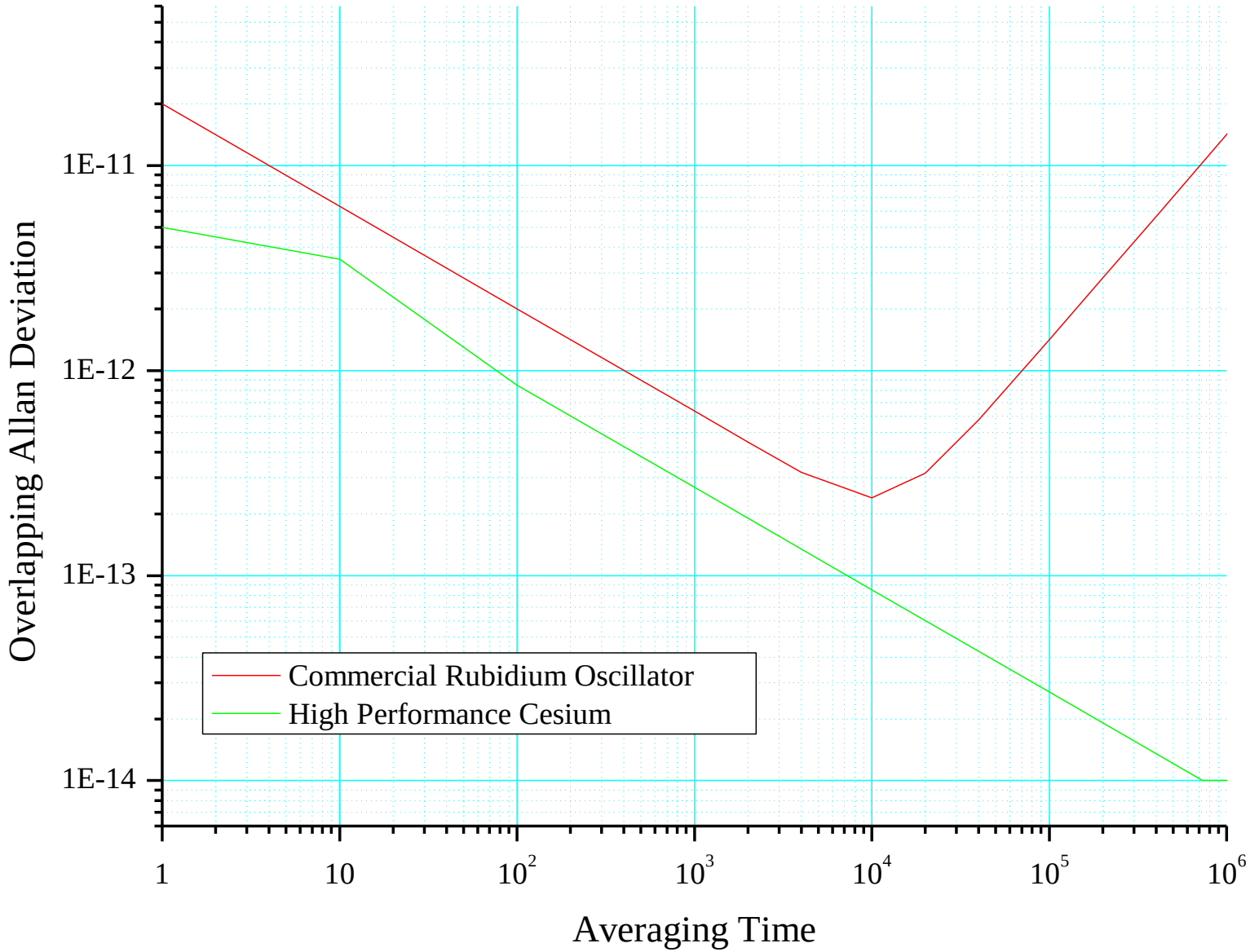
Rubidium Oscillator Summary

Symmetricom

- \+ Buffer gas confinement
  - Permits relatively narrow linewidth in small device
  - Allows for small size and economical construction
- \+ Fortuitous overlap of optical transitions between isotopes
  - Permits optical pumping with (relatively) simple discharge lamp
- \+ Long manufacturing history
  - >100,000 units deployed
  - High reliability, low cost
- \- Large frequency shift (ppm) due to collisions with buffer gas
  - Not intrinsically accurate, must be calibrated
  - Temperature sensitivity due to pressure change with temperature
  - Barometric sensitivity due to deformation of cell

- Low cost, size, and power permits widescale deployment
  - Holdover oscillator for GPS applications (<10 microseconds/day)
  - Precise time and frequency for secure communications in harsh environments.
  - Low-cost laboratory reference *(must be periodically calibrated !)*

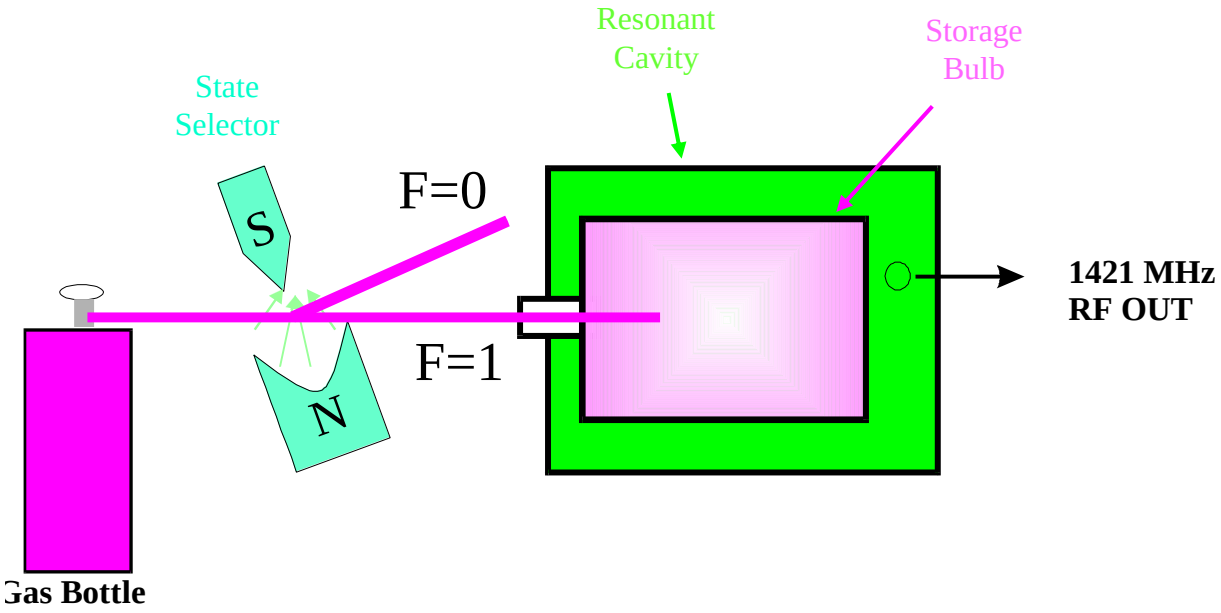
Rubidium Stability



Hydrogen Maser

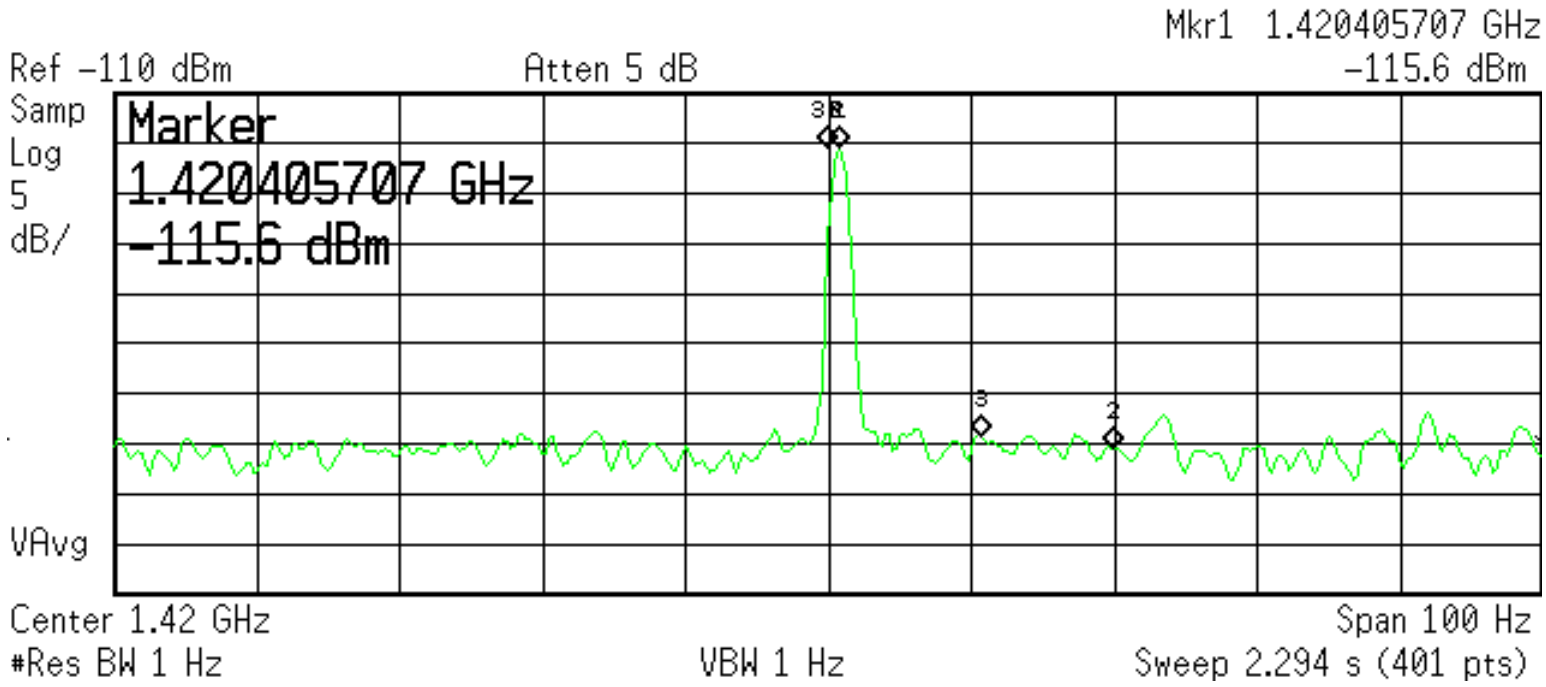
A different sort of beast

Active Hydrogen Maser



- Active Device analogous to laser
- Excellent short term accuracy (10^{-15} at 1000 s)
- Long term accuracy (10 days) drifts with cavity/wall properties

RF Spectrum

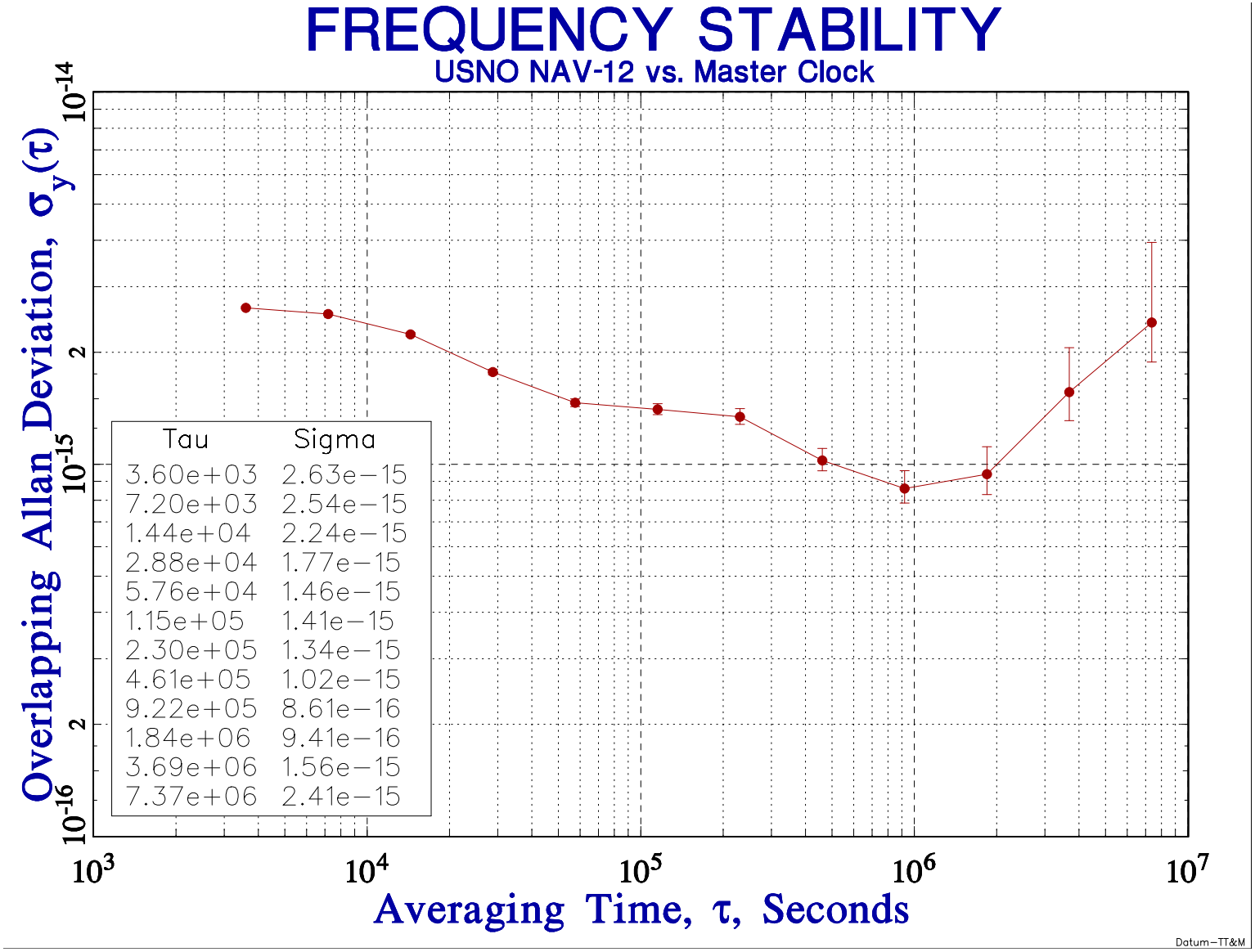


- Q is very high: ≈ (1.4 GHz/1 Hz) = 10^9 !
- Signal is very small: ≈ -110 dBm
- S/N is dominated by front-end electronic noise

Hydrogen Maser

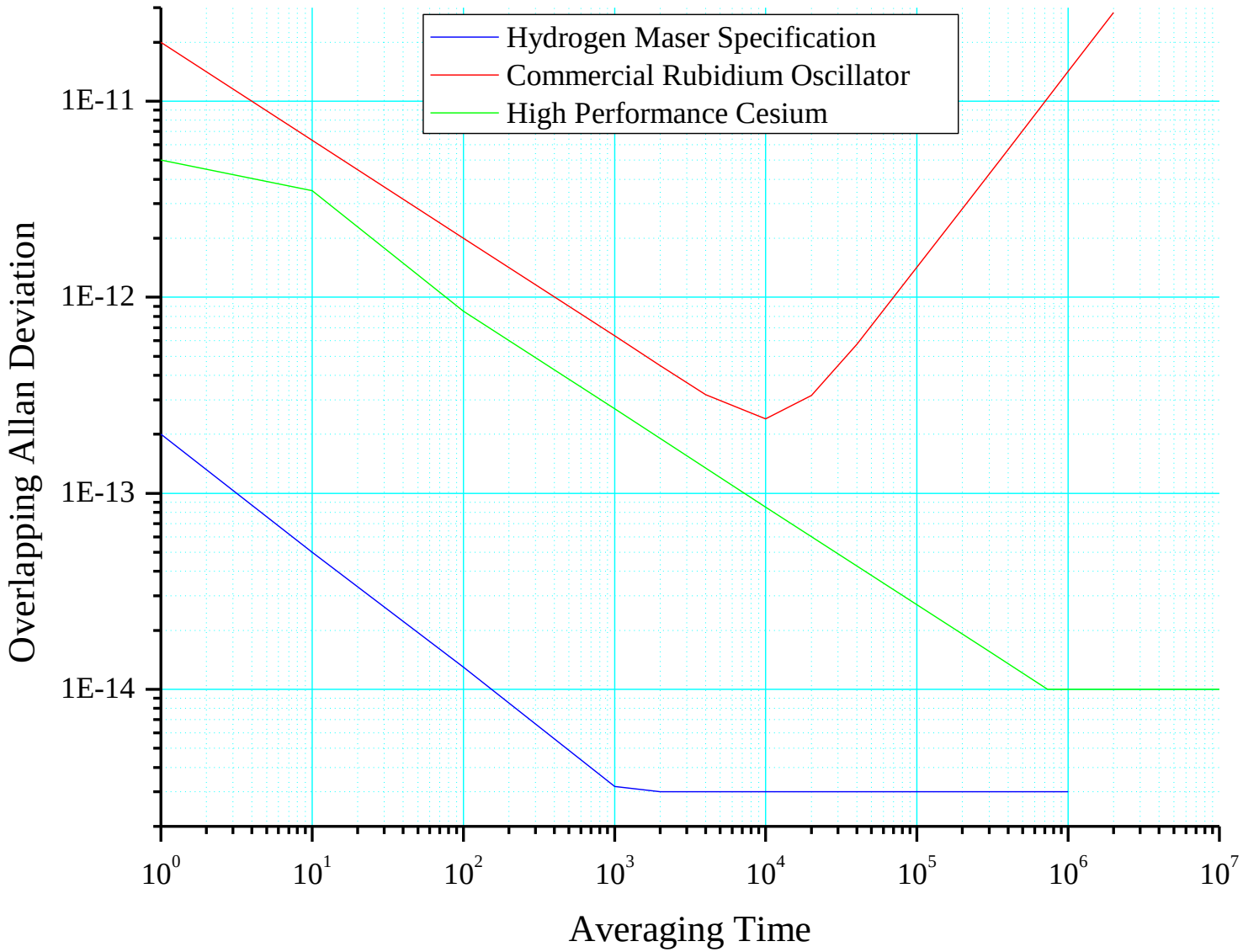
Symmetricom Model MHM2010

Long-term Stability



Tau	Sigma
3.60e+03	2.63e−15
7.20e+03	2.54e−15
1.44e+04	2.24e−15
2.88e+04	1.77e−15
5.76e+04	1.46e−15
1.15e+05	1.41e−15
2.30e+05	1.34e−15
4.61e+05	1.02e−15
9.22e+05	8.61e−16
1.84e+06	9.41e−16
3.69e+06	1.56e−15
7.37e+06	2.41e−15

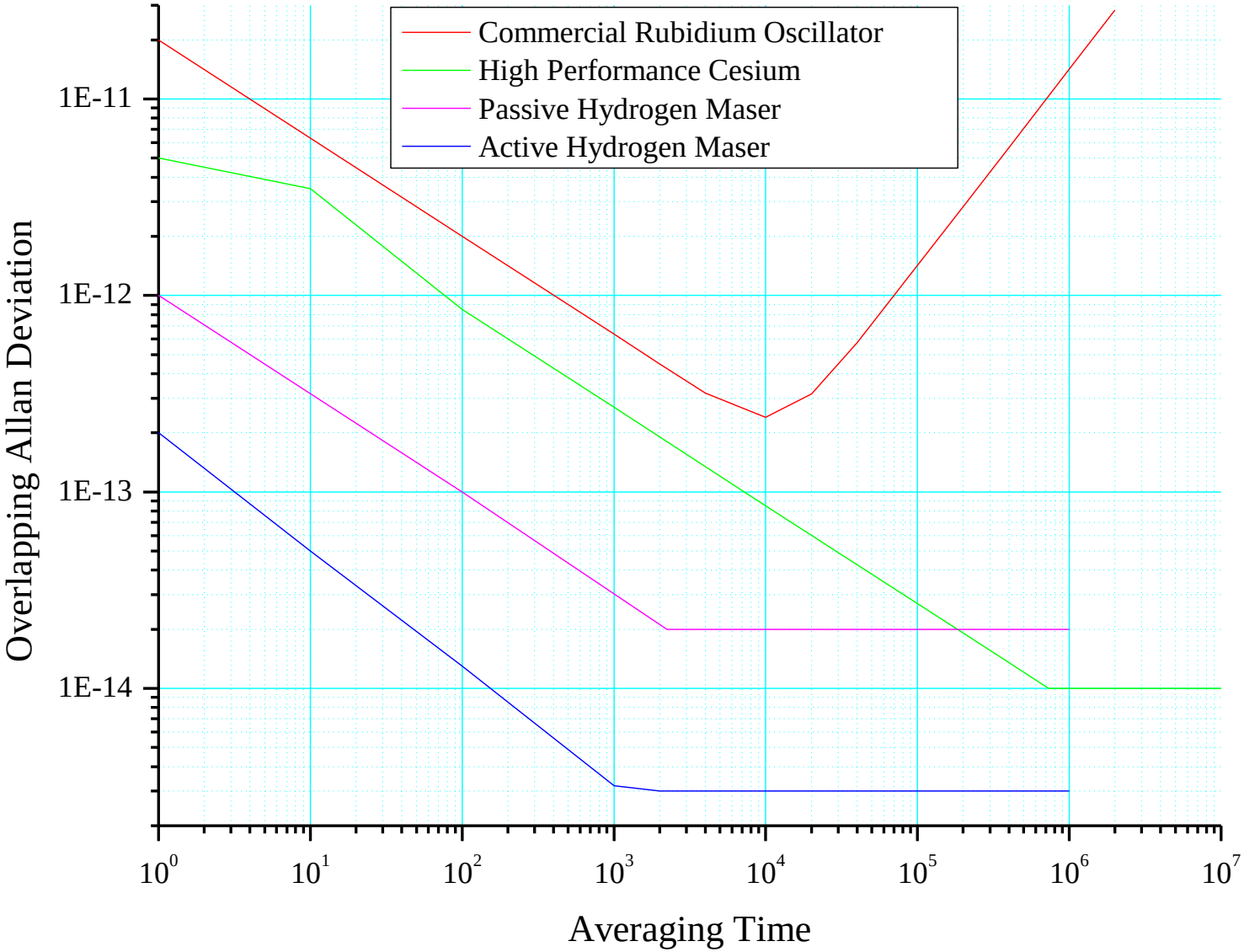
Active Hydrogen Maser Stability



Passive Hydrogen Maser

- Similar physics package to AHM but sub-threshold cavity
  - Smaller storage bulb
  - Lower-Q cavity
- Passively interrogated
  - Look for gain on transmission through population-inverted H sample
- Developed in Russia in 1960's ???
  - Now becoming available via Western brokers

Passive Hydrogen Maser Stability



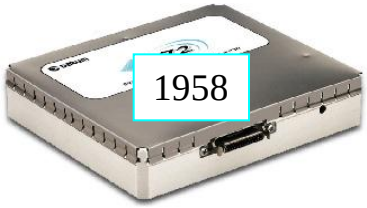
See Papers #132, 133, 134

Commercially-available atomic clocks

Symmetricom

Hydrogen maser
≈ $250K
≈ 100 W
σ_y(1 sec) ≈ 2 x 10^{-13}
Drift ≈10^{-16}/day

Cesium Beam Frequency Standard
≈ $50K
≈ 30 W
σ_y(1 sec) ≈ 10^{-11}
Drift ≈ 0



Rubidium Oscillator
≈ $2K
≈ 10 W
σ_y(1 sec) ≈ 10^{-11}
Drift ≈ 10^{-12}/day

Coherent Population Trapping (CPT)

Cyr & Tetu 1993

Symmetricom

640 IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 42, NO. 2, APRIL 1993

All-Optical Microwave Frequency Standard: A Proposal

Normand Cyr, Michel Têtu, and Marc Breton

Abstract—**We describe a simple method to produce a clock transition with purely optical means by modulated pumping. We observe the field-independent ground state resonance of ^{87}Rb atoms using sinusoidal modulation of the injection current of an AlGaAs laser diode emitting at 780 nm (FM modulation). We detect the 6.835 GHz resonance with a subharmonic modulation frequency of 1.139 GHz. A high-contrast resonance peak is observed and a condition for zero light shift is found. The linewidth is 3 kHz (at 6.835 GHz) in this preliminary experiment, due to the small size of the light beam (~2 mm diameter) and the low buffer gas pressure (680 Pa) that was used. In the first part of this article, we develop a theoretical model that explains the main features of the experiment which is described in the second part.**

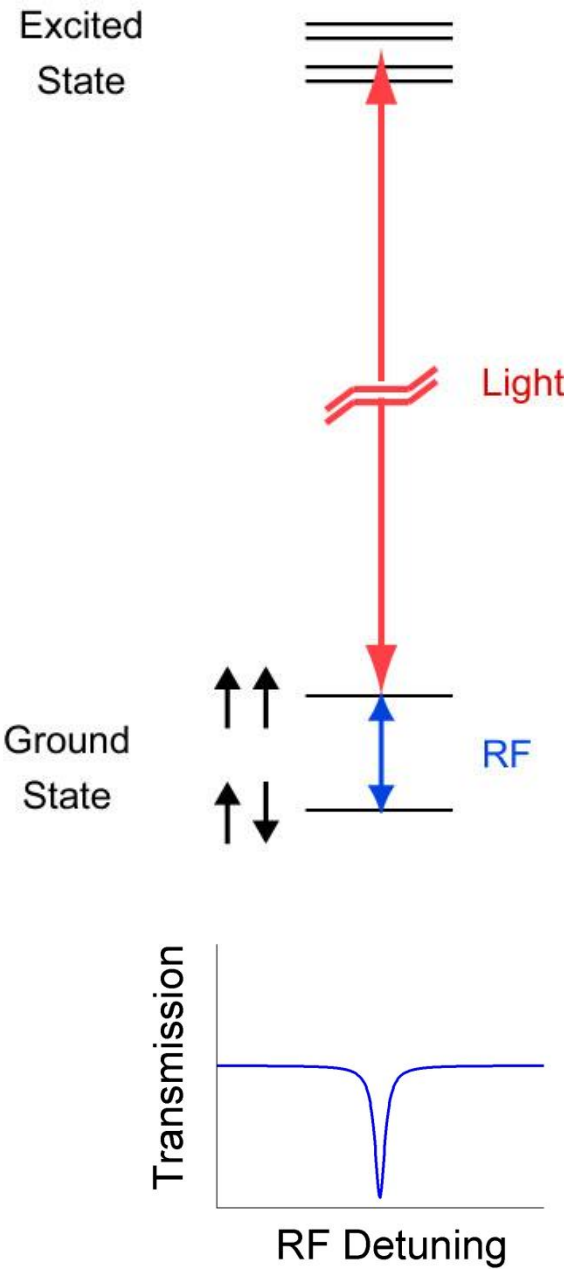
I. Introduction

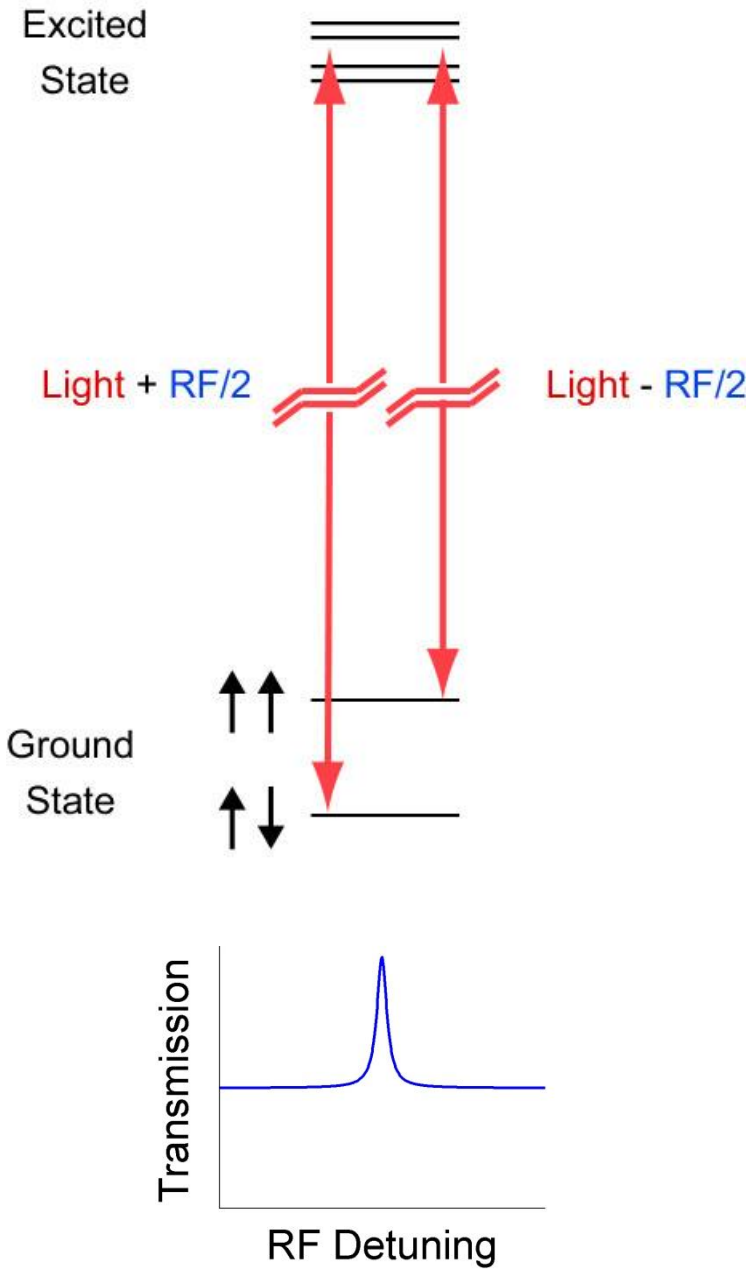
MODULATED pumping is a technique used in magnetic resonance experiments to create atomic coherences between Zeeman sublevels [1]. Within the same line of thought, resonant excitation of hyperfine coherences in alkali vapors by periodic optical pulses from a semiconductor laser permits high resolution measurements of ground state hyperfine splittings in the GHz range [2], observation of the induced hyperfine coherences using a probe beam (Section III-A).

II. Resonant Excitation of Hyperfine Coherences

In this section we make a theoretical study of the excitation of hyperfine coherences by a modulated laser beam. We consider the simple experiment described in Fig. 1. A polarized laser beam with a periodic modulation of amplitude, frequency, or phase is sent through a cell that contains a dilute gas of atoms having a ground state hyperfine structure. We calculate the steady-state hyperfine coherence induced by the laser beam with no assumption on the type of modulation or modulation waveform. In the framework that we use, periodic pulse trains or sinusoidal frequency modulation are only special cases which differ through the shape of the modulated field spectrum. In Section A, we consider atoms at rest and a simple three-level model. The addition of a buffer gas in the cell is taken into account in Section B, and the light shift and light broadening are obtained in this case. The ground state Zeeman structure is considered in Section C.

RF vs. CPT Interrogation





CPT w/Modulated diode laser

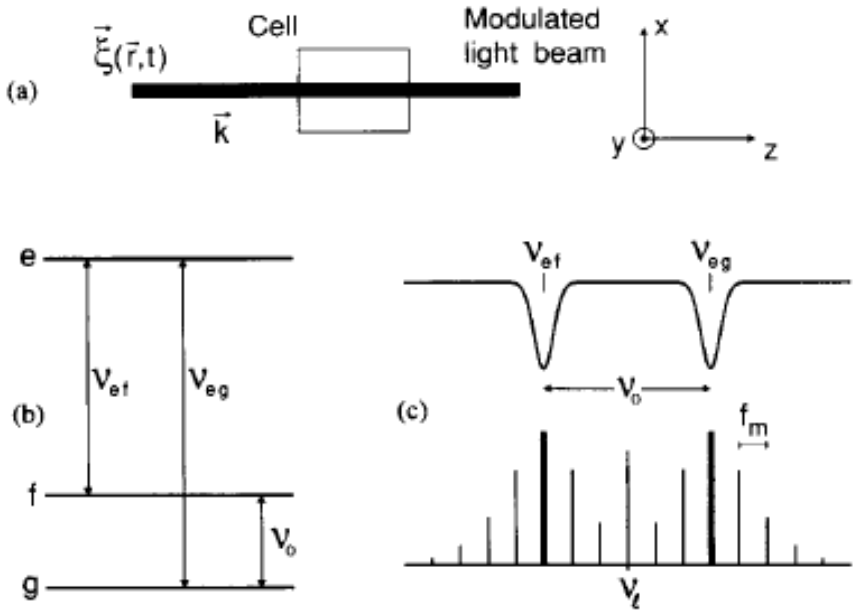
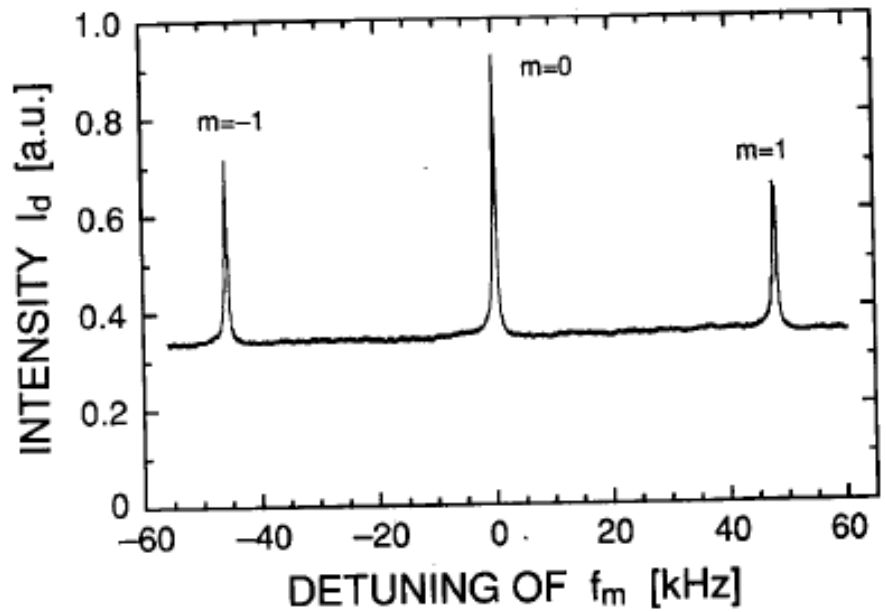
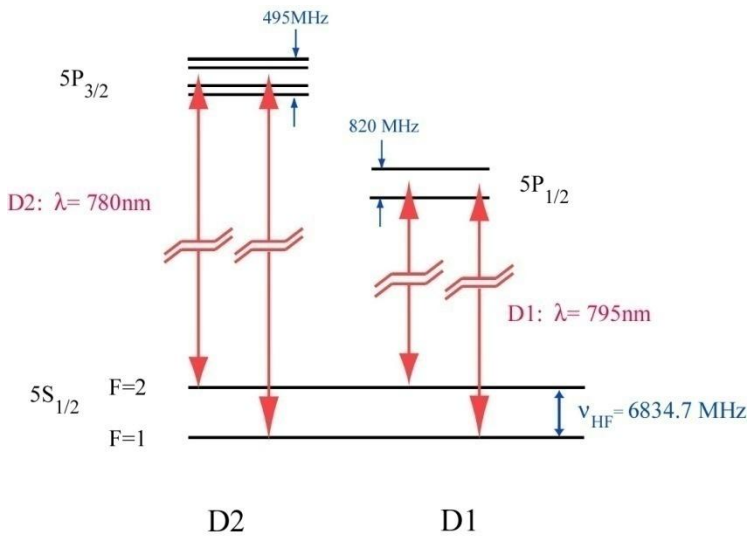


Fig. 1. Resonant excitation of hyperfine coherences by a modulated laser beam. (a) Physical situation. (b) Three-level model. (c) Example of the laser field spectrum with respect to the optical resonances ν_{ef} and ν_{eg} shown as Doppler limited linear absorption lines. Sinusoidal frequency modulation at modulation frequency $f_m = \nu_0/6$ with modulation index $\varphi = 4.2$.

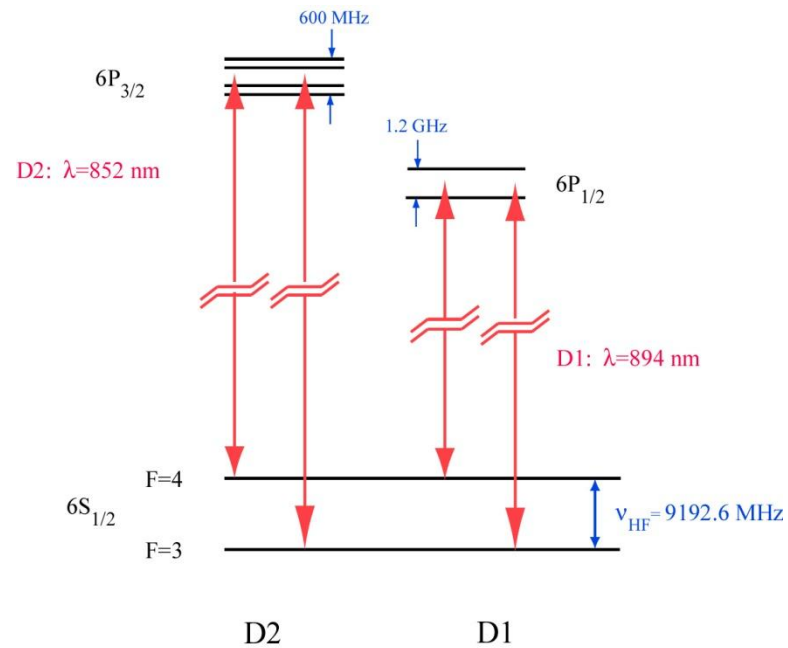


Reprinted from Cyr & Tetu 1993

Rb vs. Cs ?



^{87}Rubidium



Cesium

Fewer m_F Levels in ground state

3 vs 7 $\Delta m=0$ transitions

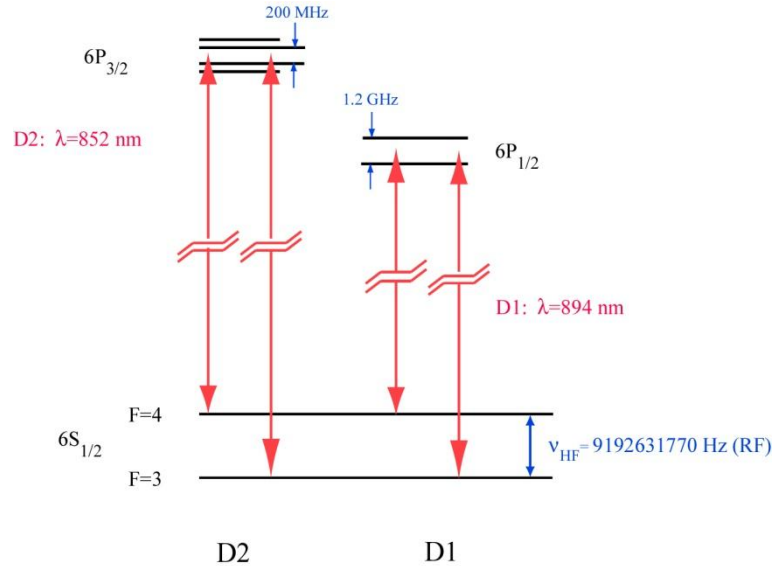
2-3X Higher vapor pressure

Higher microwave frequency (Higher Q for same γ)

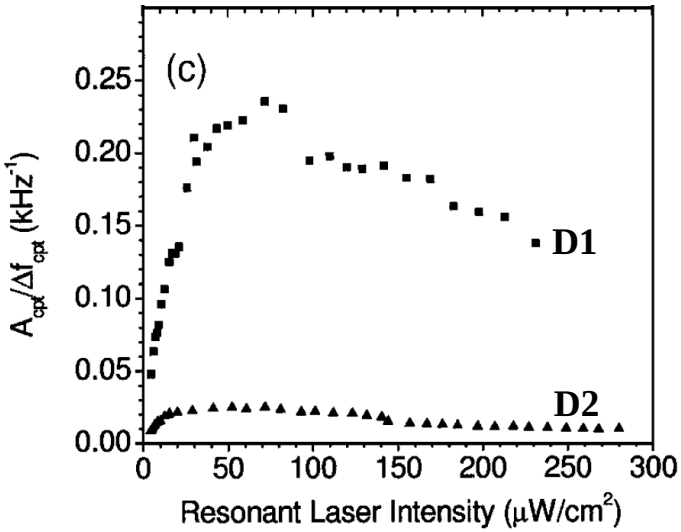
Better separation of P-states

D1 vs. D2 ?

D2 excited state multiplicity allows "leakage" of coherence via off-resonant excitation

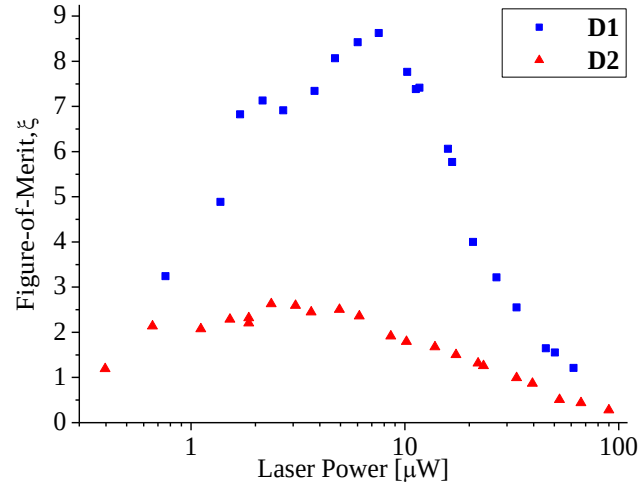


Rubidium



M. Stahler, et al., *Optics Letters*, vol. 27, pp. 1472-1474, 2002.

Cesium



R. Lutwak, et al., *PTTI 2003*

CPT clocks

KernCo CPT-C01

3.4 W, 220 cm^3

$\sigma_y(\tau) < 6 \times 10^{-11}\,\tau^{-1/2}$

Drift < 3x10^{-11}/month

From www.kernco.com

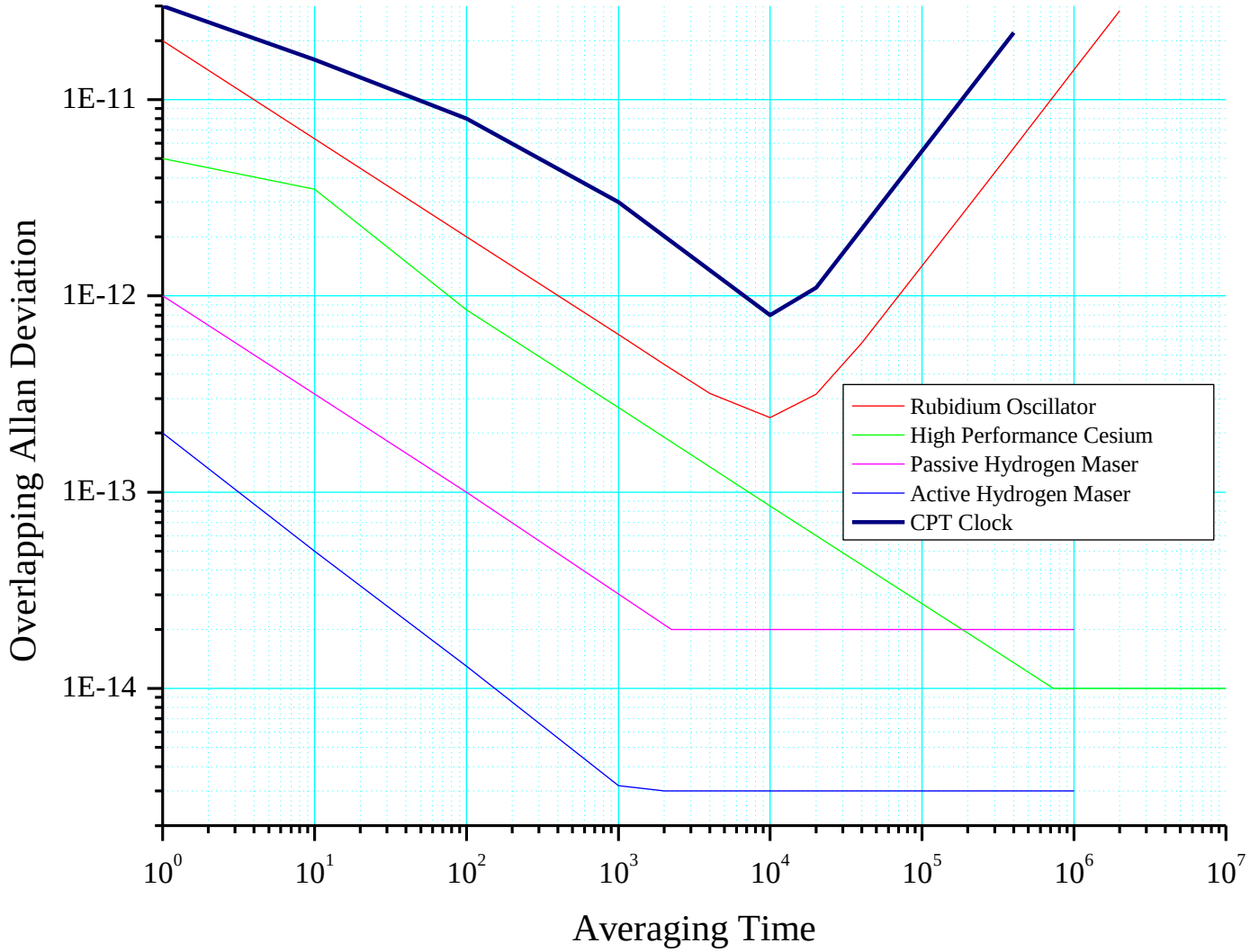
Symmetricom SA.3X.m

5 W, 46 cm^3

$\sigma_y(\tau) < 3 \times 10^{-11}\,\tau^{-1/2}$

Drift < 1x10^{-10}/month

CPT Clock Stability



See Paper #136, 143, 144, 145, 146, 148, 264, 267,

Chip-Scale Atomic Clock

Portable Battery-Power Atomic Timekeeping

1992 – Westinghouse Proposal

Symmetricom

1992 IEEE FREQUENCY CONTROL SYMPOSIUM

TOWARDS A MINIATURE LASER-PUMPED CESIUM CELL FREQUENCY STANDARD*.

P. J. Chantry, B. R. McAvoy, J. M. Zomp, and I. Liberman.

Westinghouse Science & Technology Center, Pittsburgh, PA 15235

Abstract

With the goal of minimizing the overall size of a gas cell frequency standard we have characterized cylindical Cs cells having inner dimensions R=2 mm, L=18 mm. Under conditions of present interest the lifetime in the absence of a tuned microwave field tends to be dominated by Cs-Cs collisions. Wall collisions have only a marginal effect on the lifetime provided we satisfy the approximate condition $pR^2 > 80$ Torr. mm^2 where p is the N_2/Ar buffer gas pressure. Using a TE$_{011}$ mode rectangular cavity the microwave

short term stability performance $\sigma(\tau)\tau^{1/2} \leq 1 \times 10^{-11}$. A number of authors have discussed the potential advantages of substituting laser diode pumping for the conventional discharge lamp plus filter, and the improvement in Signal-to-Noise (S/N) achievable in this way has been demonstrated [3,4,5]. The potential for improving the overall performance has been explored in depth by Camparo and Frueholz [6] using a theoretical model of the device, taking into account the noise characteristics of available laser diodes.

If one plans to minimize the total package size

- Proposed laser-pumped miniature cesium clock
- Calculations of optimal buffer gas mix for narrow linewidth in small cell
- Predict $\sigma_y(\tau) \approx 5 \times 10^{-12}\, \tau^{-1/2}$

THE WALL STREET JOURNAL.
WEDNESDAY, AUGUST 30, 1995
VOL. LXXVI NO. 223

TECHNOLOGY

Atomic Clock Designed by Westinghouse Is Smaller, Cheaper, but Still Precise

By RAJU NARISETTI
Staff Reporter of THE WALL STREET JOURNAL

PITTSBURGH—**Westinghouse Electric** Corp. has designed a low-cost, walnut-sized atomic clock that promises to significantly expand the use of these sophisticated timepieces in military and commercial applications.

Atomic clocks are used primarily in electronic devices that transmit data, allowing, for instance, two computers on opposite sides of the globe to exchange information accurately.

Westinghouse researchers say their patented "ultraminiature" clock will be one-tenth the size of—and 100 times lighter than — any atomic clock now available and will sell for about $1,000, compared with existing clocks that can sell for as little as about $3,000 but typically cost more than $10,000.

Because the new clocks are so small and inexpensive, they could, for instance, be placed in all base stations for cellular phone companies, as opposed to a few spotty centers. Westinghouse says the additional clocks would provide improved signal stability that would allow more subscribers on the system and also reduce the signal fadeout that occurs when a mobile caller travels from one base station to another.

Atom Acts as Pendulum

Atomic clocks, in which an atom takes on the role of a pendulum, are used more to synchronize than to tell time and were first developed in the 1960s. The name comes from their use of the frequency of oscillation of certain atoms (often cesium) to maintain an electronic circuit.

The clocks are also used in global positioning satellites where positions on earth are determined by measuring how long it takes radio signals to travel between a satellite and a receiver. The precise clocks allow several satellites to work together to triangulate the exact position of a given receiver on earth.

But up to now receivers generally use less-expensive and less-accurate crystal oscillators. Westinghouse hopes its new atomic clocks could be placed on the receivers, significantly enhancing performance in guiding artillery shells to land on targets with pinpoint accuracy or for commercial aircraft to locate runways under zero visibility conditions.

Irving Liberman, a program manager at Westinghouse's Pittsburgh-based Science and Technology Center, says the company was able to develop such a small clock by combining integrated electronic circuits with inexpensive lasers, such as those used in a compact disk player, to "excite the cesium atoms."

Big Lamps, Big Clocks

Conventional atomic clocks, which use rubidium, a silvery metallic element, use large lamps to create the same heat effect, making them bulky. Dr. Liberman notes that NIST-7, a seventh-generation atomic clock developed at the National Institute of Standards and Technology two years ago, is a cylinder 10 feet long and 1.5 feet in diameter.

"We were able to reduce the size, cost and the power, and yet keep the performance," he says. Westinghouse initially plans to use the clock for defense applications at its Baltimore-based electronic systems unit. Westinghouse is also trying out other military applications under a three-year, $3 million program funded by the federal government's Advanced Research Projects Agency.

Westinghouse also plans to explore commercial licensing opportunities for the clock, particularly in telecommunications applications where the market leader is Efratom, a unit of **Datum** Inc., Anaheim, Calif. Efratom is the inventor and world's largest supplier of atomic clocks that use rubidium.

David Leksell, microsystems commercialization manager at Westinghouse, estimates some 50,000 atomic clocks could be sold over the next few years to the telecommunications industry. "The ones that are out there are too large and costly to have a pervasive impact now," he says.

Westinghouse researchers say their patented "ultraminiature" clock will be one-tenth the size of—and 100 times lighter than — any atomic clock now available and will sell for about $1,000, compared with existing clocks that can sell for as little as about $3,000 but typically cost more than $10,000.

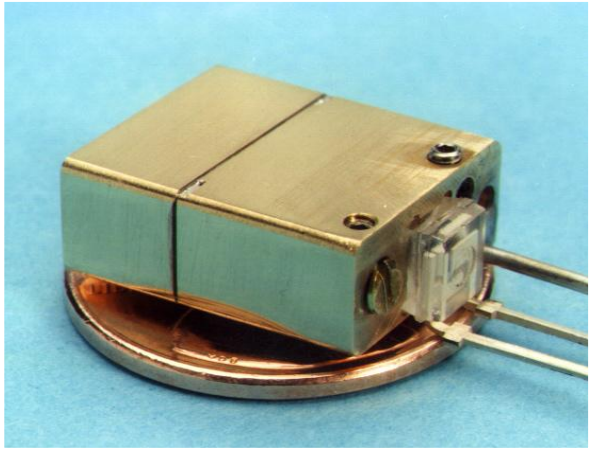
oscillators. Westinghouse hopes its new atomic clocks could be placed on the receivers, significantly enhancing performance in guiding artillery shells to land on targets with pinpoint accuracy or for commercial aircraft to locate runways under zero visibility conditions.

Reprint courtesy of Irv Liberman

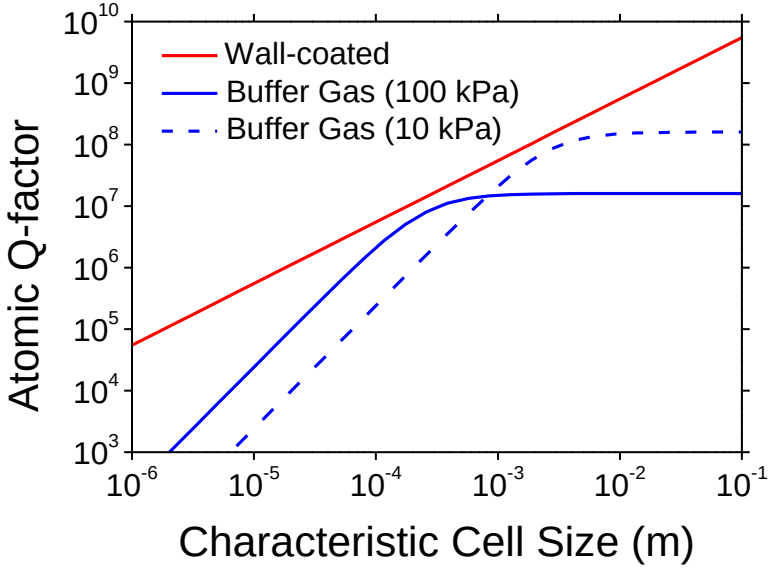
Westinghouse/NG – the first CSAC effort

Symmetricom

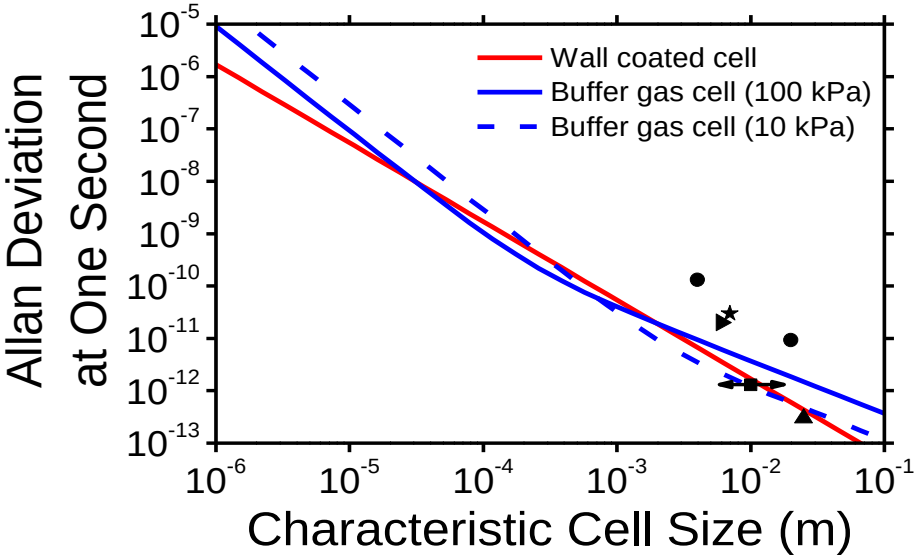
- 1991 - ≈1999
- Cesium vs. Rubidium
  - Smaller cavity
  - Availability of laser diodes
  - Higher vapor pressure
- Dielectrically-loaded 9.2 GHz TE_{201} cavity
- Diode laser for optical pumping
  - Funded development of STM VCSEL
- Optimized buffer gas mixtures
  - S/N, linewidth
  - Temperature coefficient
- Achieved 200 mW physics package:
  - 16 cm^3
  - $\sigma_y(\tau) \approx 2 \times 10^{-11} \tau^{-1/2}$
  - Drift ≈ 1×10^{-10}/month



Physics in REALLY small cells?



J. Kitching, S. Knappe, and L. Hollberg, "Performance of small-scale frequency references," presented at IEEE International Frequency Control Symposium, New Orleans, LA, 2002.



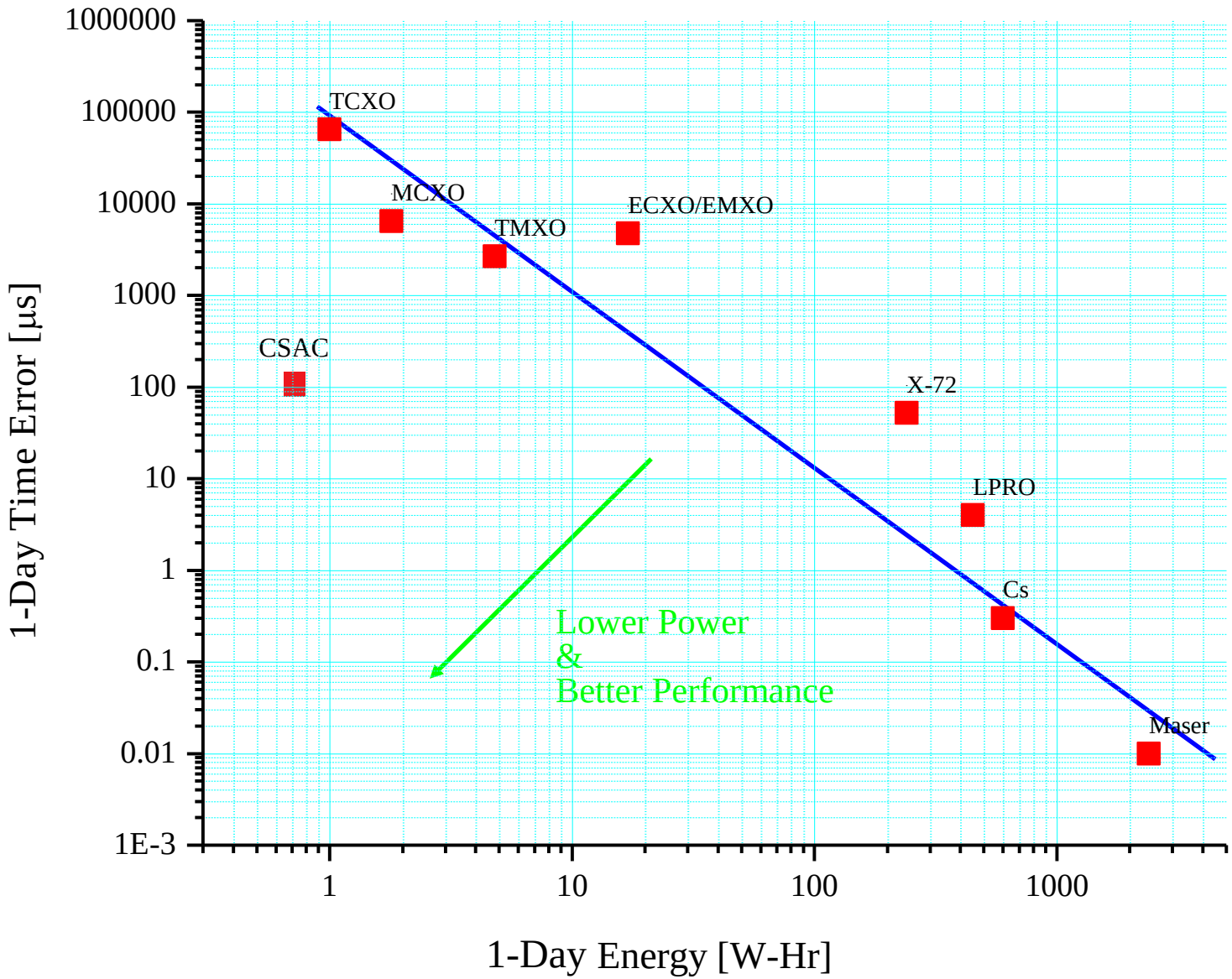
J. Kitching, S. Knappe, and L. Hollberg, "Miniature vapor-cell atomic-frequency references," *Applied Physics Letters*, vol. 81, pp. 553-555, 2002.

Applications

- Cannot compete with GPS time for cost, power, or size
  - "GPS-denied" environments
  - Consumer applications are VERY cost-sensitive

    However cool it is, you CANNOT put a $1000 CSAC in a $200 television set
- Secure Communications
  - Time-Sequence Code Acquisition in GPS-denied environments
- Enhanced GPS receivers
  - Navigation with <4 Satellites
  - Rapid P(y) code acquisition (military)
- Underwater timing applications
  - Data-logging, beacons, etc.
- Ad-hoc timing and navigation networks
  - In-building, downtown (first responders, military)
  - Automobile collision avoidance systems
- High-bandwidth communications
  - Video-on-demand, teleconferencing, etc.

The CSAC Challenge

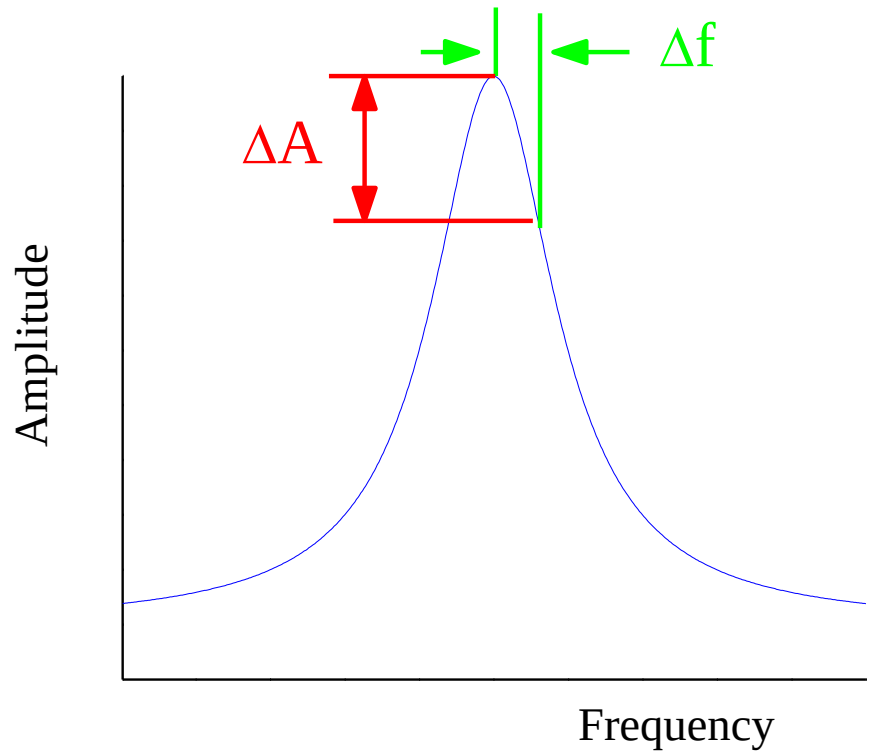


Major Challenges

- Physics Package
  - Must be heated to T≈85°C to vaporize (alkali metal) atoms
    - Thermal isolation – *Convection, Conduction, Radiation*
    - Overhead heat load – *Low-power-dissipation VCSEL*
  - Mechanical Robustness
    - Shock and vibration resistance for handheld (dropped) applications
- Microwave Synthesizer
  - Phase noise at microwave frequency (4.6 GHz) must support Signal/Noise
  - Short-term stability at $\tau < \tau_{LOOP}$ must support STS objective
  - Must be tunable with 10^{-11} resolution (50 mHz) for calibration
  - Output must be useful to customer – *10.0 MHz, spectral purity, …*
- Control Systems
  - Short-term stability – *Low-noise components, Optimum interrogation*
  - Long-term stability – *"Independent" stabilization of interrogation environment*
    - Atom density and buffer gas environment, optical power and spectrum
- Value
  - Size, power, stability
  - …long-term stability…environmental stability…ease of integration…cost…

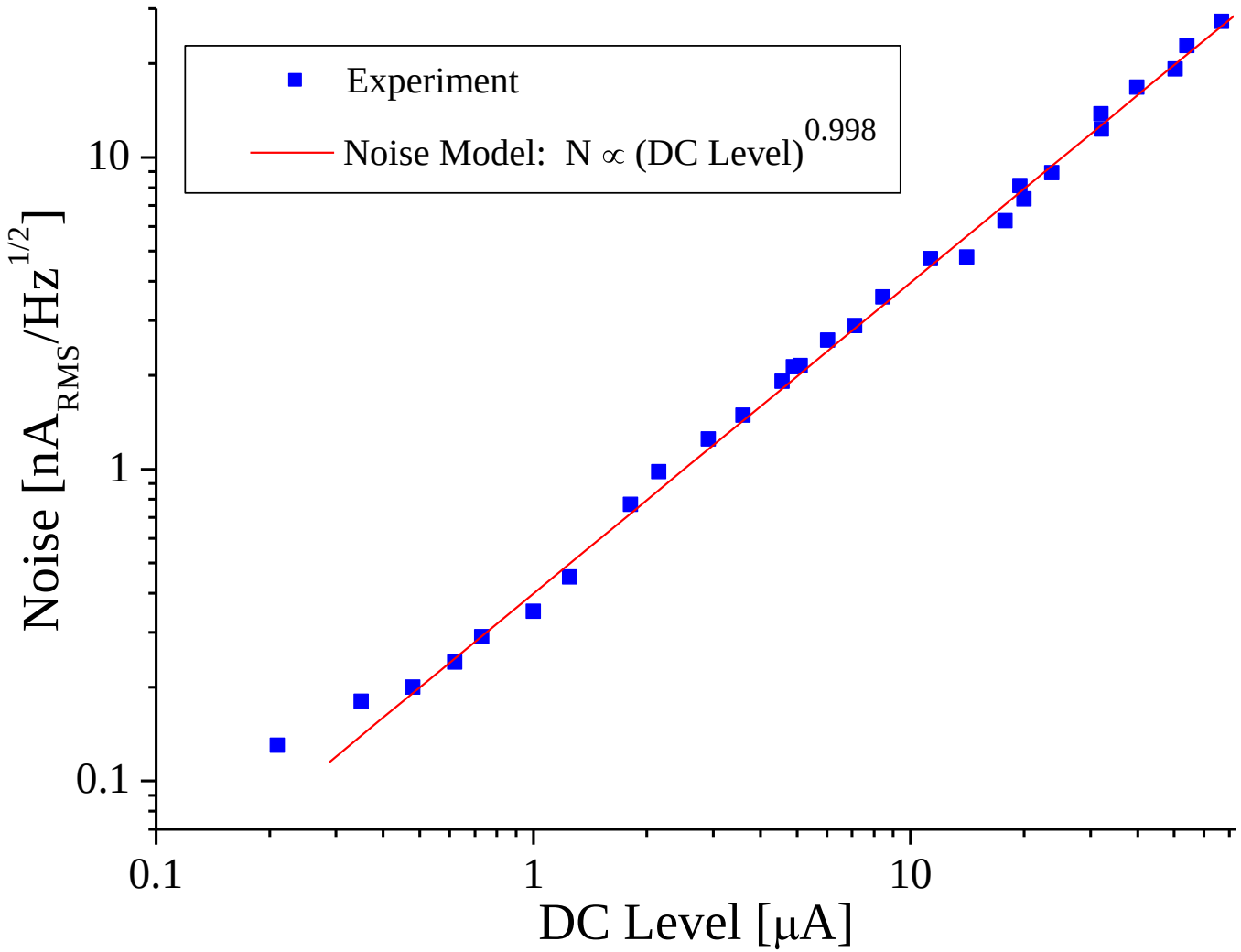
Physics Package

Noise Contributions



- Laser Noise ∝ DC Level
- Statistical (Shot) Noise ∝ (DC Level)$^{1/2}$
- Local Oscillator phase noise ∝ (Discriminator slope)
- Pre-amplifier current and voltage noise (constant)
- Other Electronics (constant)

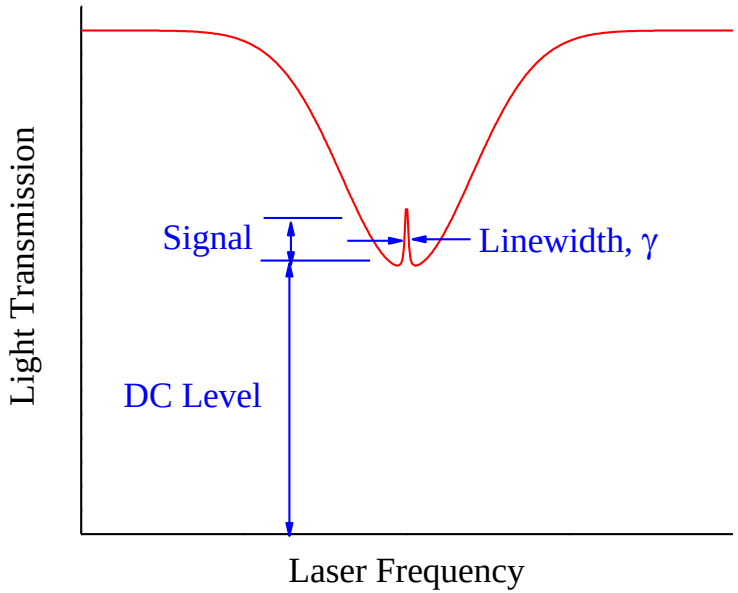
Noise vs. Laser Power



∴ Laser Frequency Noise Dominates

Noise ∝ DC Level

Figure-of-Merit



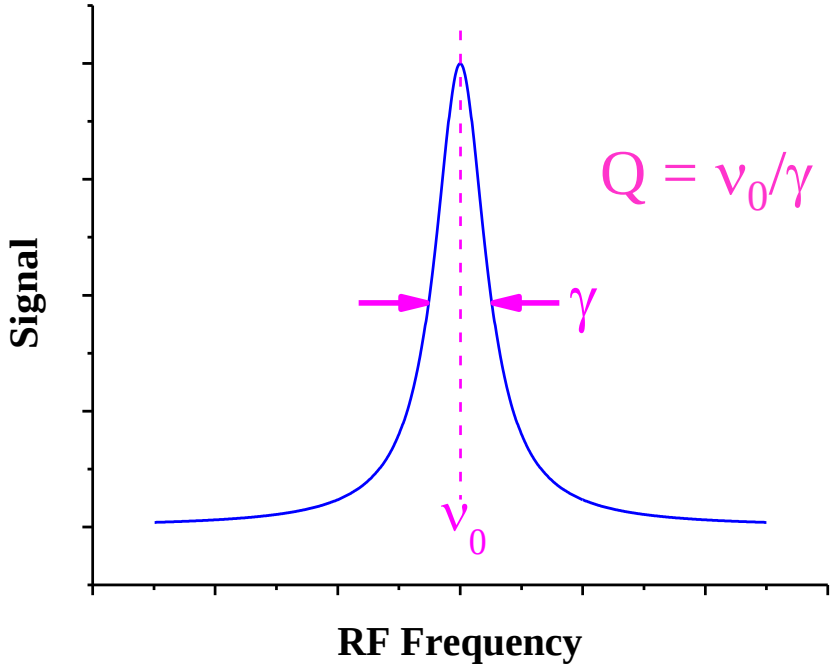
Contrast: $\eta \equiv$ Signal/DC Level

Figure-of-Merit: $\xi \equiv \eta / \gamma$

Then:

$$\sigma_y(\tau) \propto \left(\frac{1}{\xi}\right)\tau^{-1/2}.$$

PP Short-term stability

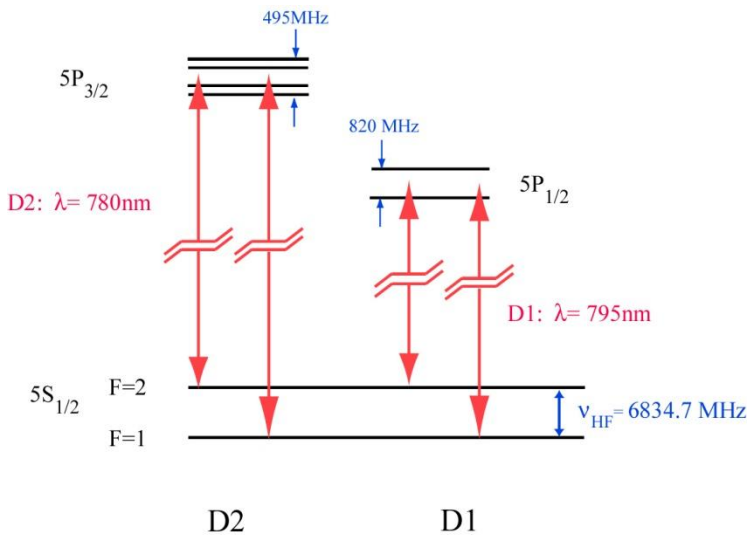


Equation 1 revisited:

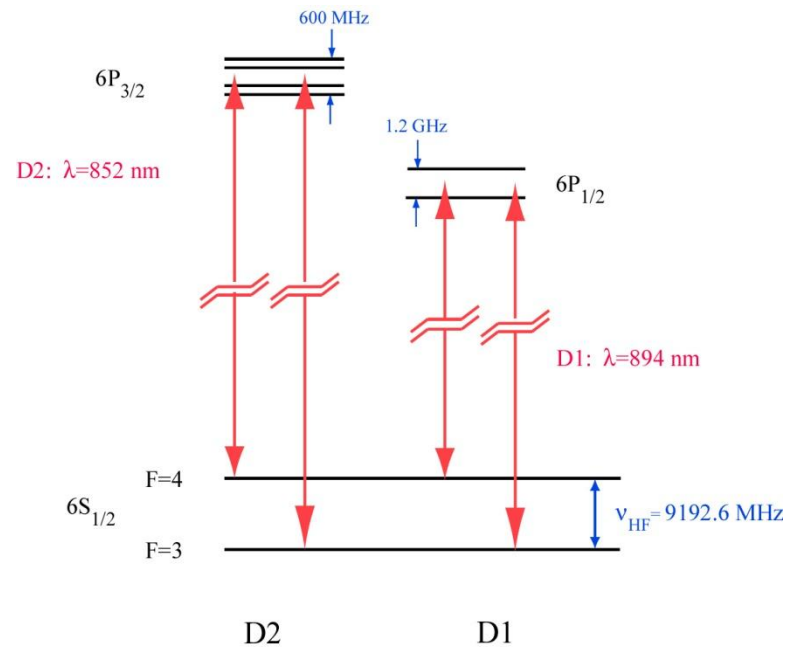
$$\sigma(\tau) = \frac{1}{(S/N)_\tau \times Q}$$

- Q?
  - ν_0 from choice of atom
  - γ from collisions (atom-atom, atom-buffer gas, atom-wall), laser power, …
- S/N?
  - Signal: Choice of atom, laser spectrum/polarization, buffergas optimization,…
  - Noise: photon shot noise, atom shot noise, laser noise, electronic noise, …

Rb vs. Cs ?



^{87}Rubidium



Cesium

Fewer m_F Levels in ground state
3 vs 7 Δm=0 transitions

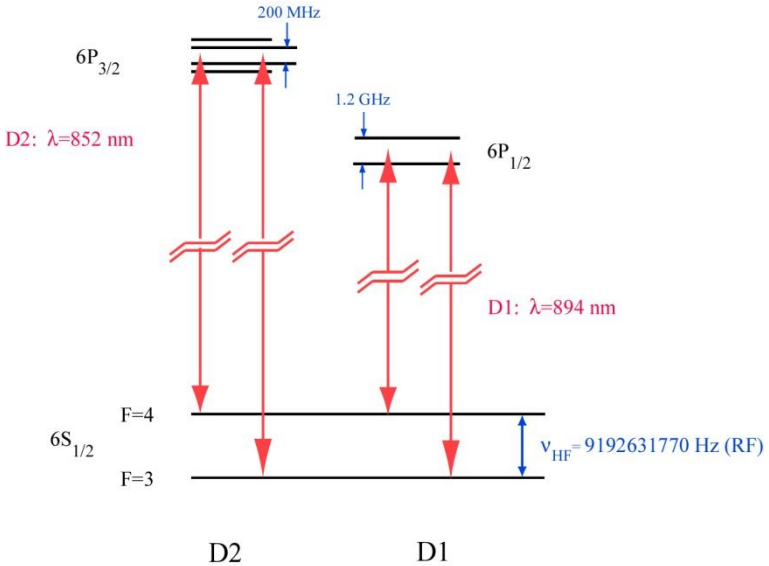
NIST, Honeywell, Teledyne

2-3X Higher vapor pressure
Higher microwave frequency
Better separation of P-states *(less important for CSAC)*
Laser availability *(less important in 2008)*

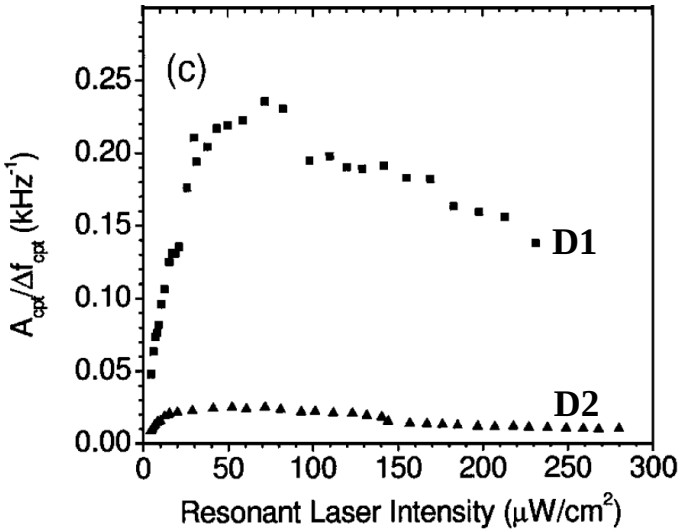
NIST, Symmetricom, Sarnoff, Westinghouse

D1 vs. D2 ?

D2 excited state multiplicity allows "leakage" of coherence via off-resonant excitation

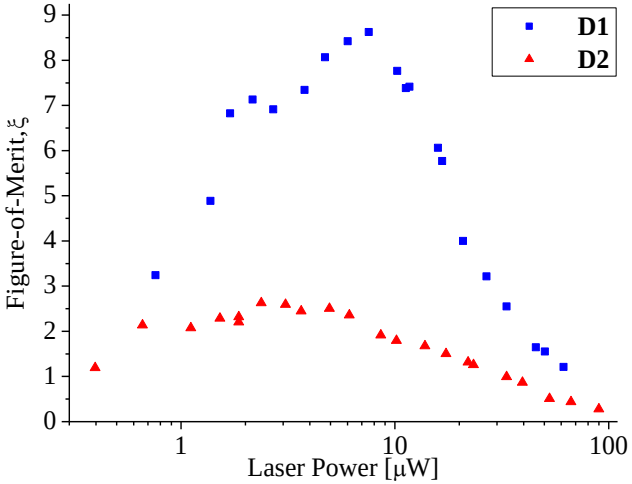


Rubidium



M. Stahler, et al., *Optics Letters*, vol. 27, pp. 1472-1474, 2002.

Cesium

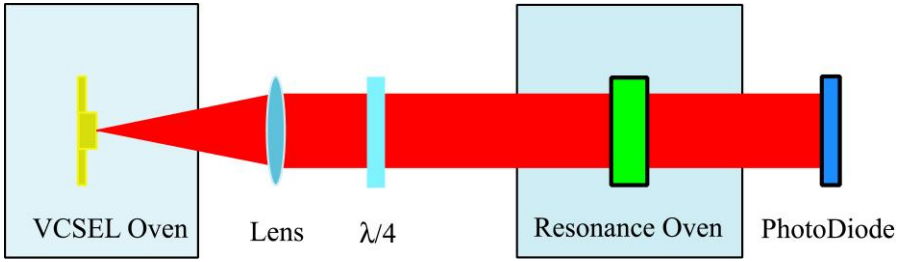


R. Lutwak, et al., *PTTI 2003*

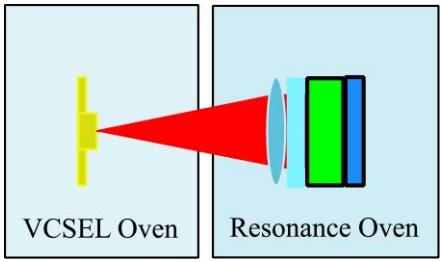
Physics Package Objectives

- Size: $< 1\ cm^3$
- Power: $< 20\ mW$
- Reliability: $MTBF > 10^5$ *Hours*
- Ruggedness: *1000 G shock, 2* G_{RMS} *Vibration*
- Performance: $\xi > 1$

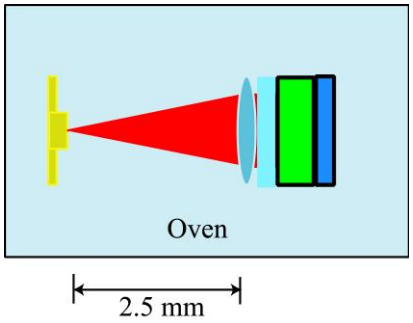
Small CPT



Typical Laboratory Setup

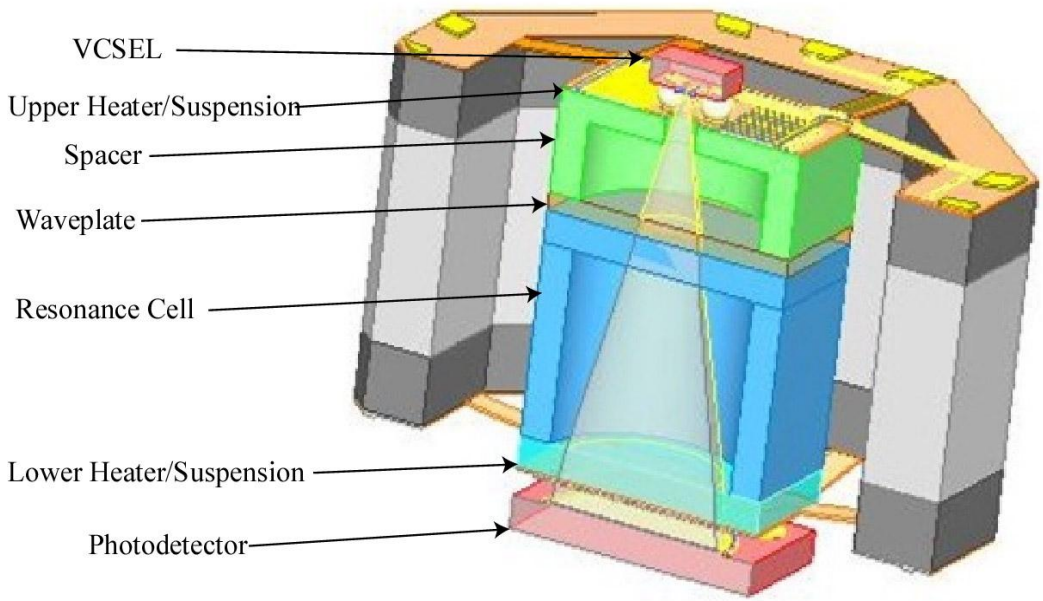


Minimum Component Spacing



Single Oven:
VCSEL must tune to $\lambda_{cesium}@T_{cell}$

The Draper 10 mW Physics Package



US Patent #7215213

- Tensioned polyimide suspension
- Microfabricated Silicon vapor cell
- Low-power Vertical-Cavity Surface Emitting Laser (VCSEL)
- Vacuum-packaged to eliminate convection/conduction
- Overall Thermal Resistance 7000°C/W

M. Mescher, et. Al., "An Ultra-Low-Power Physics Package for a Chip-Scale Atomic Clock," *Proceedings of the 13th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '05)*, Seoul, Korea, June 5-9, 2005, pp. 311-316.

Laser Requirements

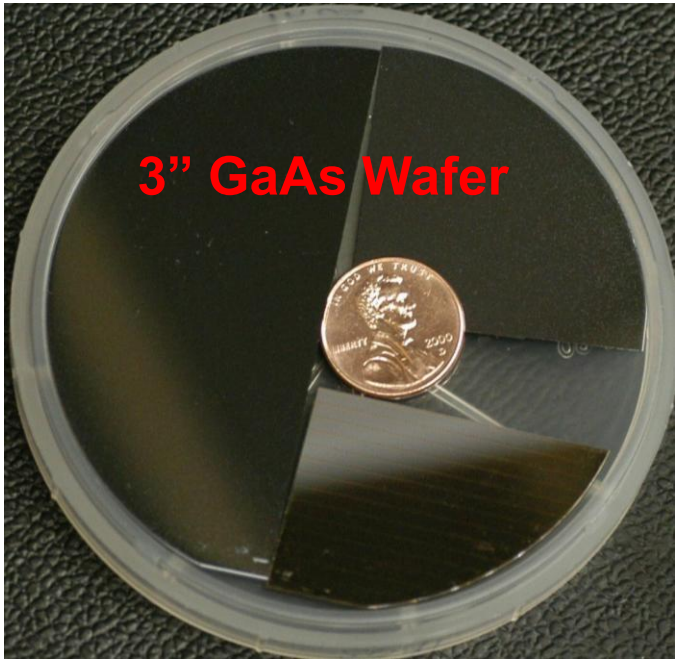
- Must tune to atomic wavelength
- Must stay there (with servo) for life of clock
- Pure polarization state
- Single longitudinal- and transverse-mode
- Low amplitude noise
- Low frequency noise (narrow linewidth)
- High FM bandwidth (for CPT)
- Low Power dissipation

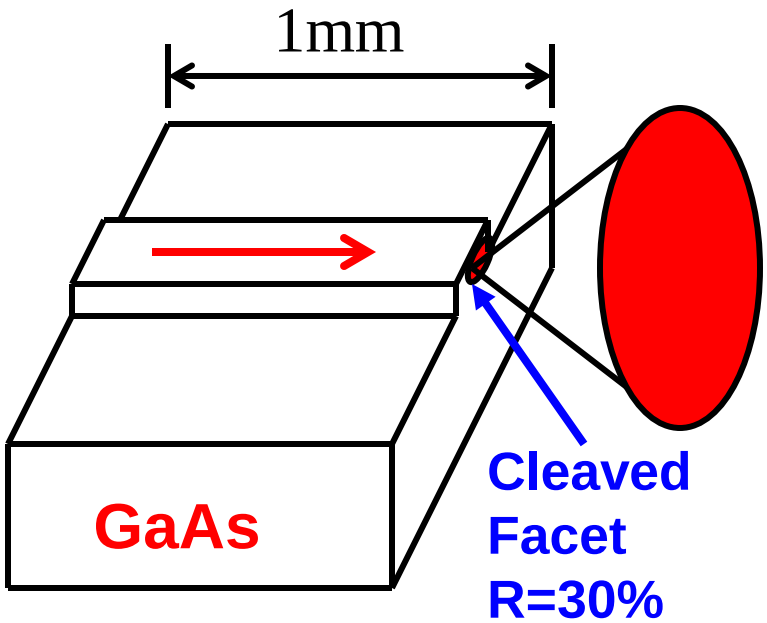
Edge-emitting Lasers

Symmetricom

Optical Gain: Compound Semiconductors (GaAs)

Epitaxial Layer Growth





Pros:

- **Simple Crystal Growth**
- **Narrow linewidth (< 5 MHz)**

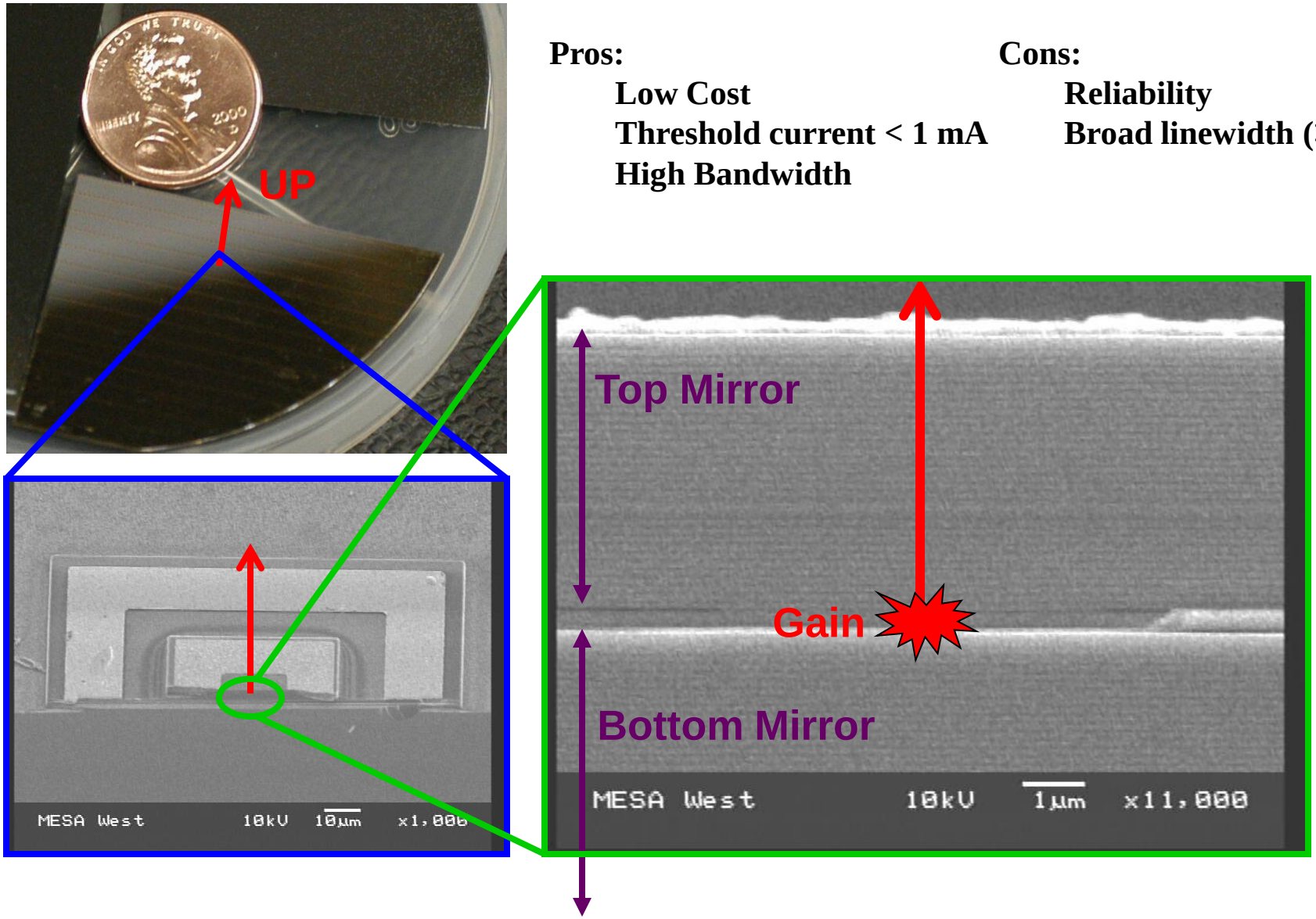
Cons:

- **Cleave before test**
- **Elliptical Beam**
- **Longitudinal Cavity Mode hops**
- **High threshold current (>30 mA)**

Courtesy of Darwin Serkland, Sandia National Laboratories

Vertical-Cavity Surface-Emitting Lasers

Symmetricom



Pros:

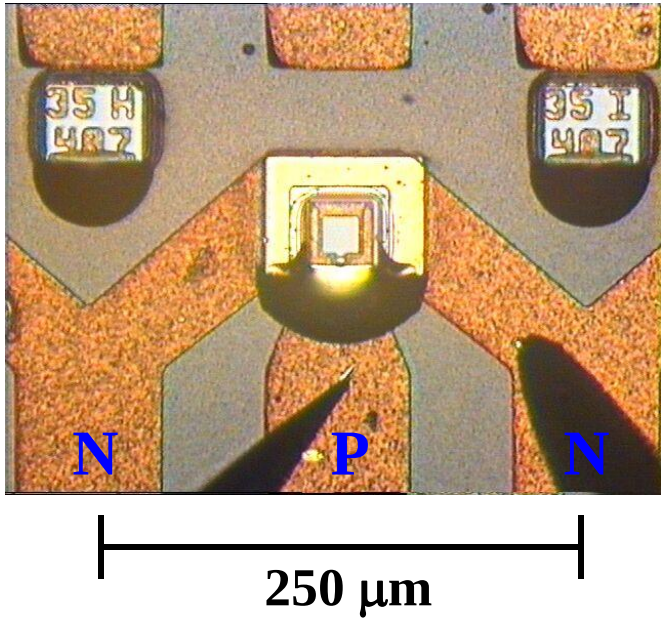
- Low Cost
- Threshold current < 1 mA
- High Bandwidth

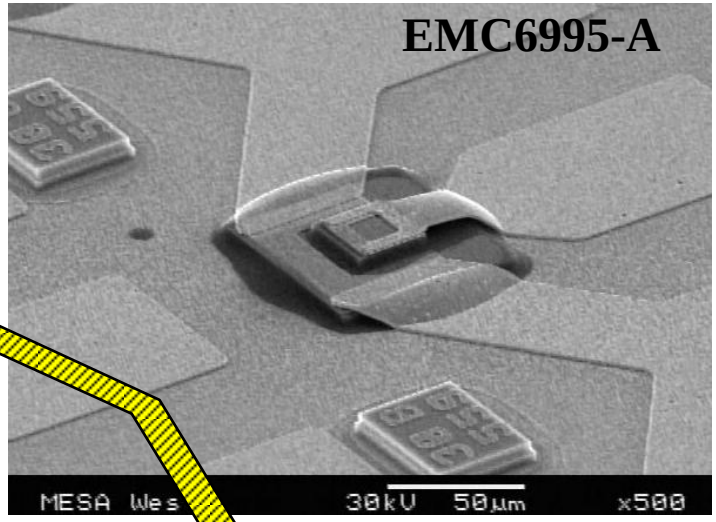
Cons:

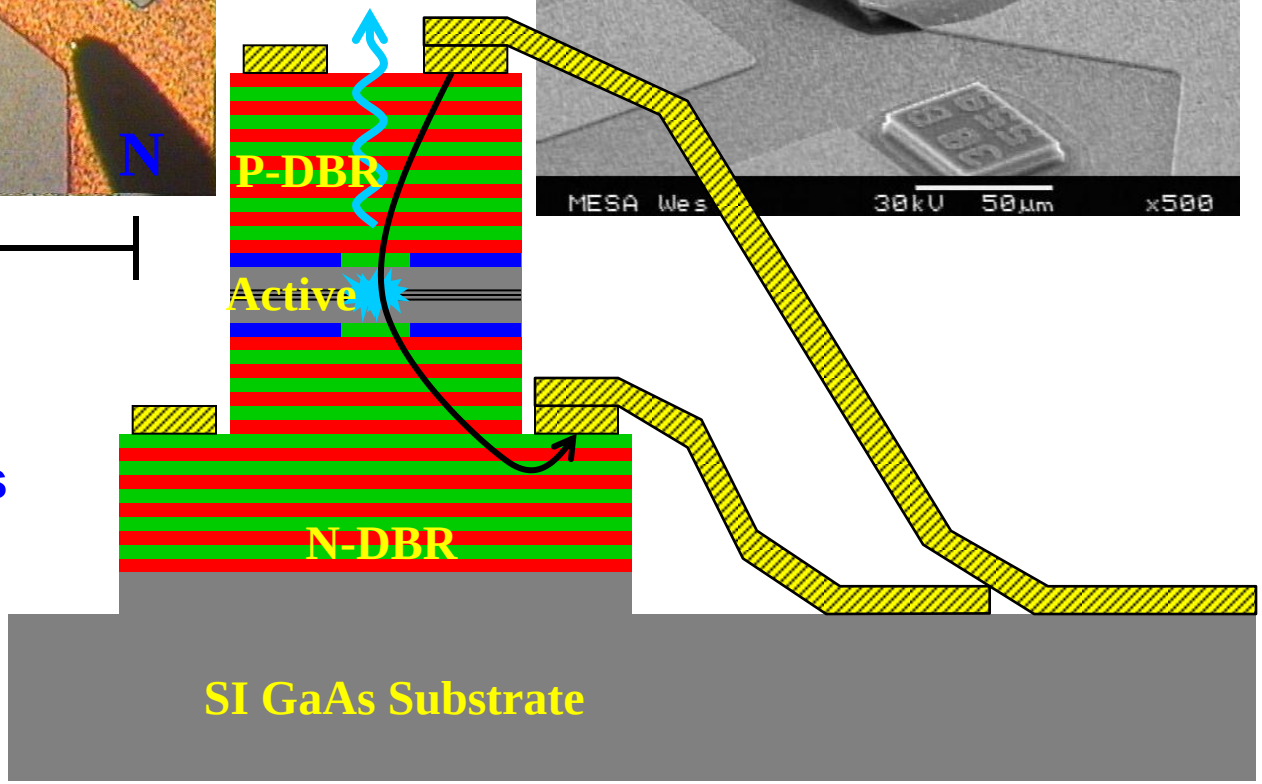
- Reliability
- Broad linewidth (>50 MHz)

Courtesy of Darwin Serkland, Sandia National Laboratories

VCSEL Fabrication and Operation



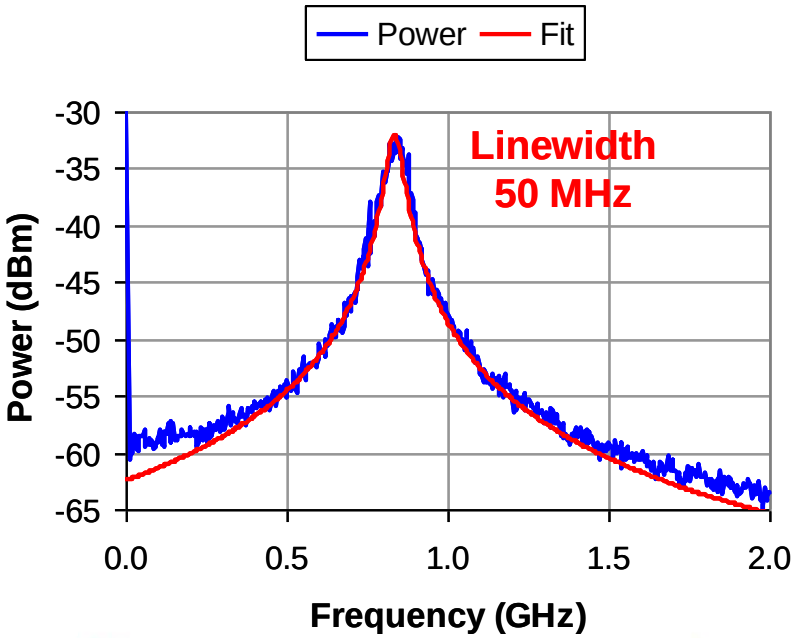


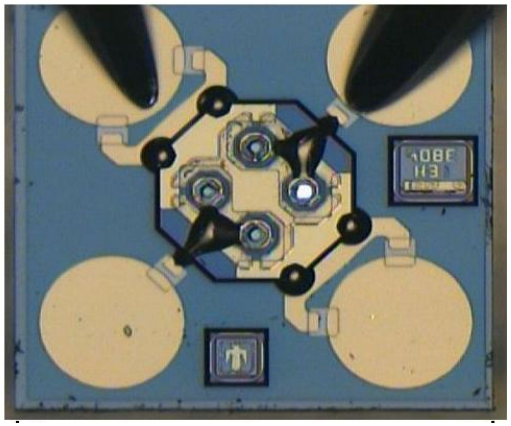


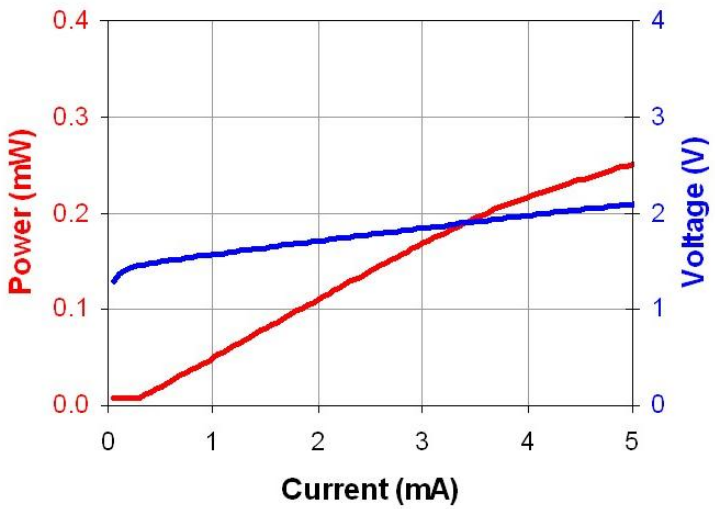
1994: Selective Oxidation of AlAs

Courtesy of Darwin Serkland, Sandia National Laboratories

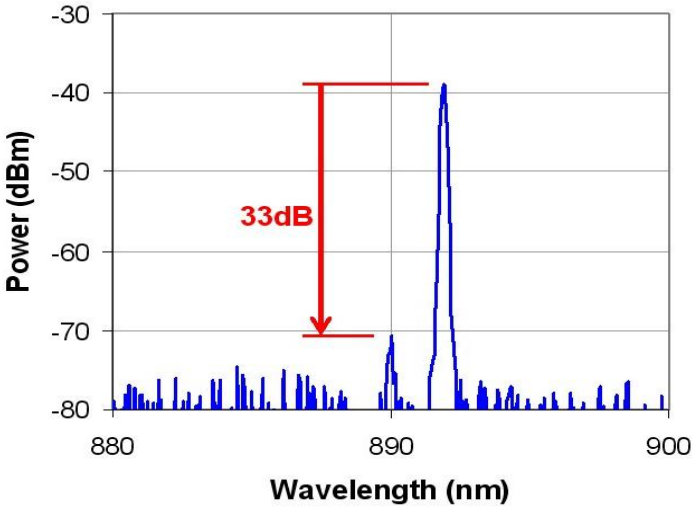
Sandia Cs D1 VCSEL @ 894 nm







Side-mode suppression



D.K. Serkland, et. al., "*VCSELs for Atomic Sensors*", Proceedings of the SPIE, Vol. 6484, 2007.

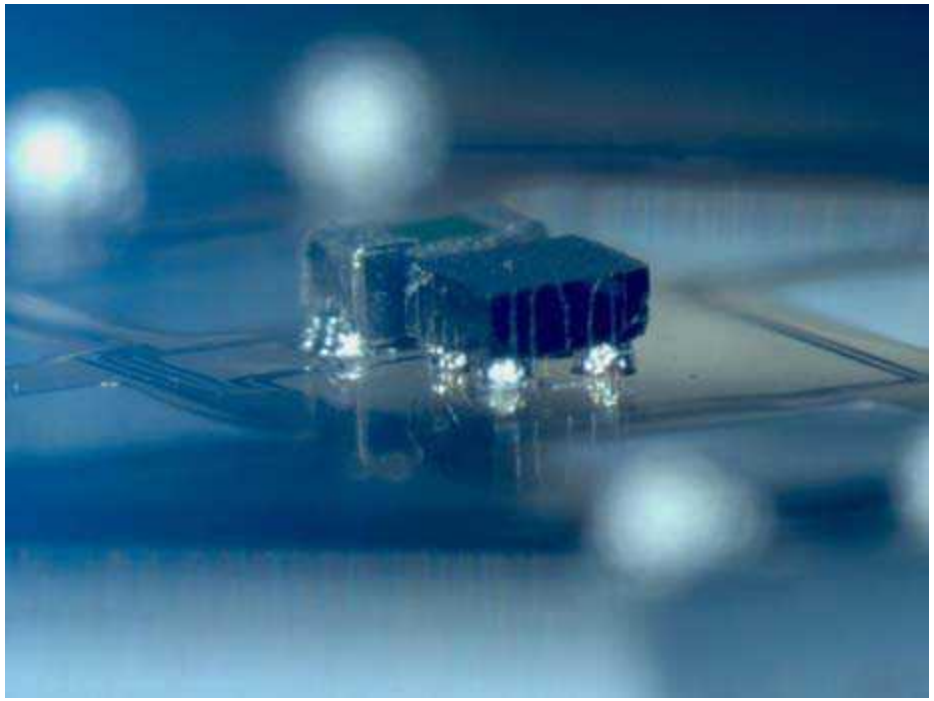
Polyimide Suspension

Symmetricom

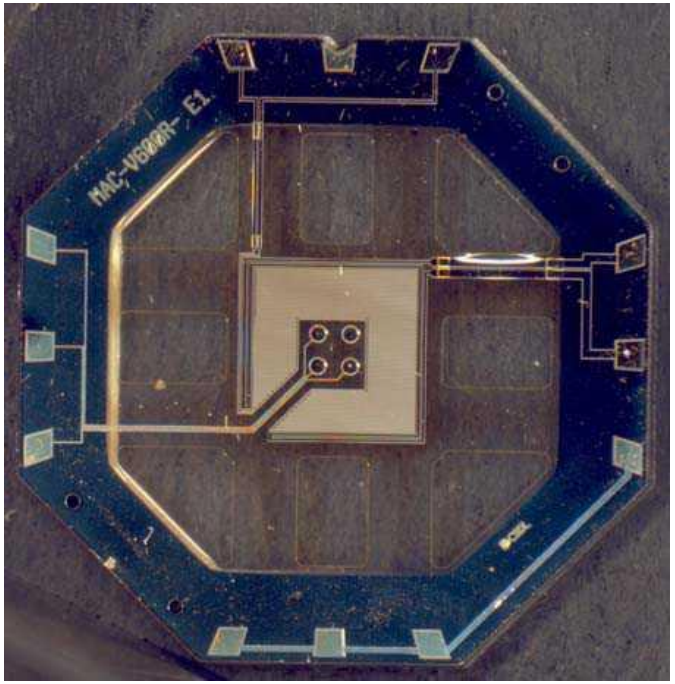
- Excellent material
  - Low thermal conductivity: *0.2 W/m ℃*
  - High yield strength: *3%*
- Electrical traces patterned onto polyimide
  - Metals need not be mechanically self-supporting for reduced cross-section and thermal conductivity
- Fabrication:
  - Spin-on 5 μm polyimide on Si wafer
  - Photodefinition/liftoff to pattern polyimide
  - Sputter Ti/Pt and Ti/Pt/Au, and Ti/Au metalization
  - Backside etch Si to release polyimide suspension and octagonal “frames”
- Alternate fabrication by die-cut or laser-cut of polyimide film

M. Mescher, et. Al., "An Ultra-Low-Power Physics Package for a Chip-Scale Atomic Clock," *Proceedings of the 13th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '05)*, Seoul, Korea, June 5-9, 2005, pp. 311-316.

Polyimide Suspension



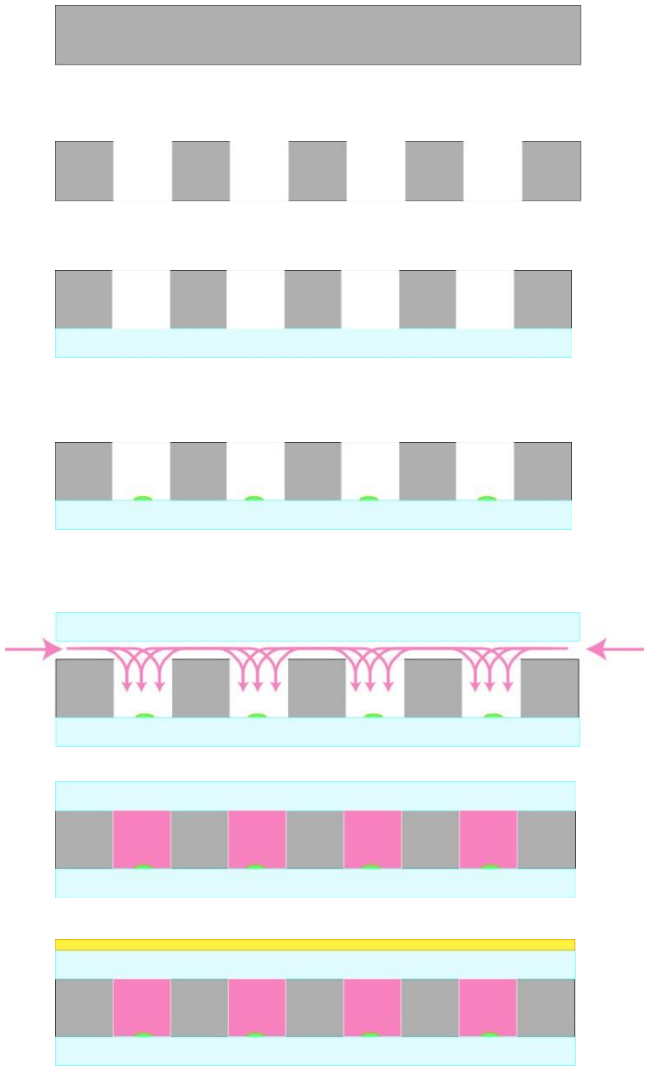
VCSEL and Thermistor on Polyimide suspension



Polyimide suspension

Photos courtesy of Draper Laboratory

Resonance Cell Fabrication



Start with 1.5 mm thick Silicon

DRIE 1.5 mm diameter holes

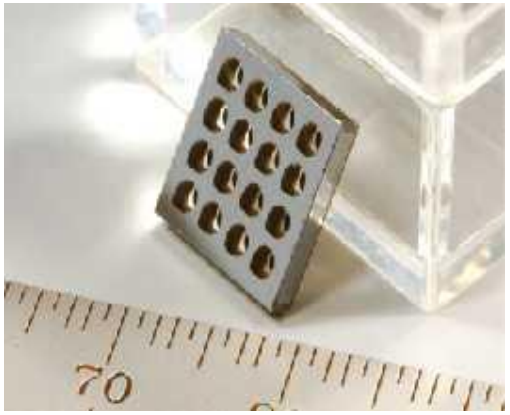
Anodic bond bottom window

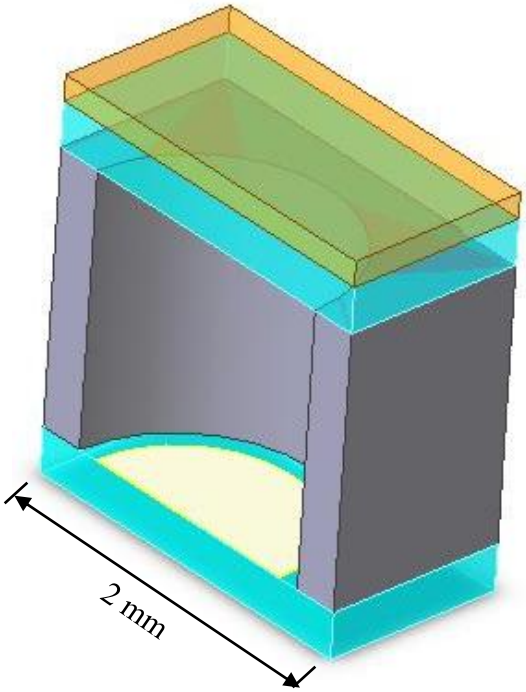
Diffusive transfer Cs into wells

Evacuate & backfill w/buffer gas

Anodic bond top window

Epoxy bond Waveplate





Dice

How to get Cs/Rb into cells?

Symmetricom

- NIST: $BaN_6 + RbCl \rightarrow BaCl + 3N_2 + Rb$
  - L. Liew, et al, "Microfabricated alkali atom vapor cells," *Applied Physics Letters* **48**, 2004
- NIST: Atomic Beam in vacuum
  - S.Knappe, et al, "Atomic vapor cells for chip-scale atomic clocks with improvel long-term frequency stability," *Optics Letters*, **30**, 2005
- Draper/Symmetricom: Diffusive transfer through N_2
  - M. Mescher, et. Al., "An Ultra-Low-Power Physics Package for a Chip-Scale Atomic Clock," *Proc. 13th Intl. Conf. on Solid-State Sensors, Actuators and Microsystems, 2005*
- Princeton/Sarnoff: Electrolysis of "cesiated" glass
  - F.Gong, et al, "Electrolytic fabrication of atomic clock cells," *Rev.Sci.Inst.* **77**, 2006
- Sarnoff: Pin Transfer
  - M.H.Kwakernaak, et al, "Component for Batch-Fabricated Chip-Scale Atomic Clocks," *Proc. 36th PTTI*, 2004
- Cornell(?): Wax pellets

Buffer Gas

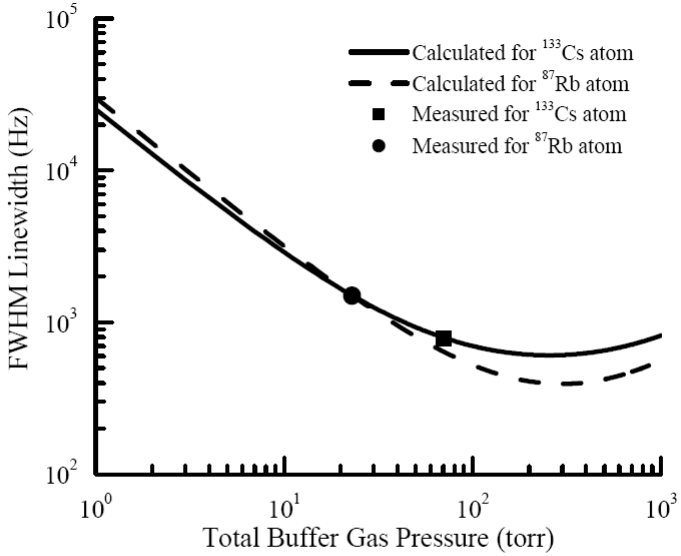


Figure 7. Comparison between the calculated linewidths and the measure linewidths for both ^{133}Cs atom and ^{87}Rb atom. The Cs absorption cell is a micro-machined Si cell (diameter = 1.7 mm, length = 2 mm). The Rb cell is a all glass cell (diameter = 2 mm, length = 2 mm). See text for discussion.

From: Zhu, et al., FCS 2004

Buffer gas "immobilizes" atoms to reduce Doppler broadening of microwave resonance ("Dicke narrowing") and to reduce dephasing due to collisions with cell walls.

"Shift" of resonance frequency is ≈ kHz/Torr

Fortunately, some buffer gases cause + or – shifts and + or – change in shift with temperature

Gas mixtures can eliminate either total shift or temperature dependence (but not both)

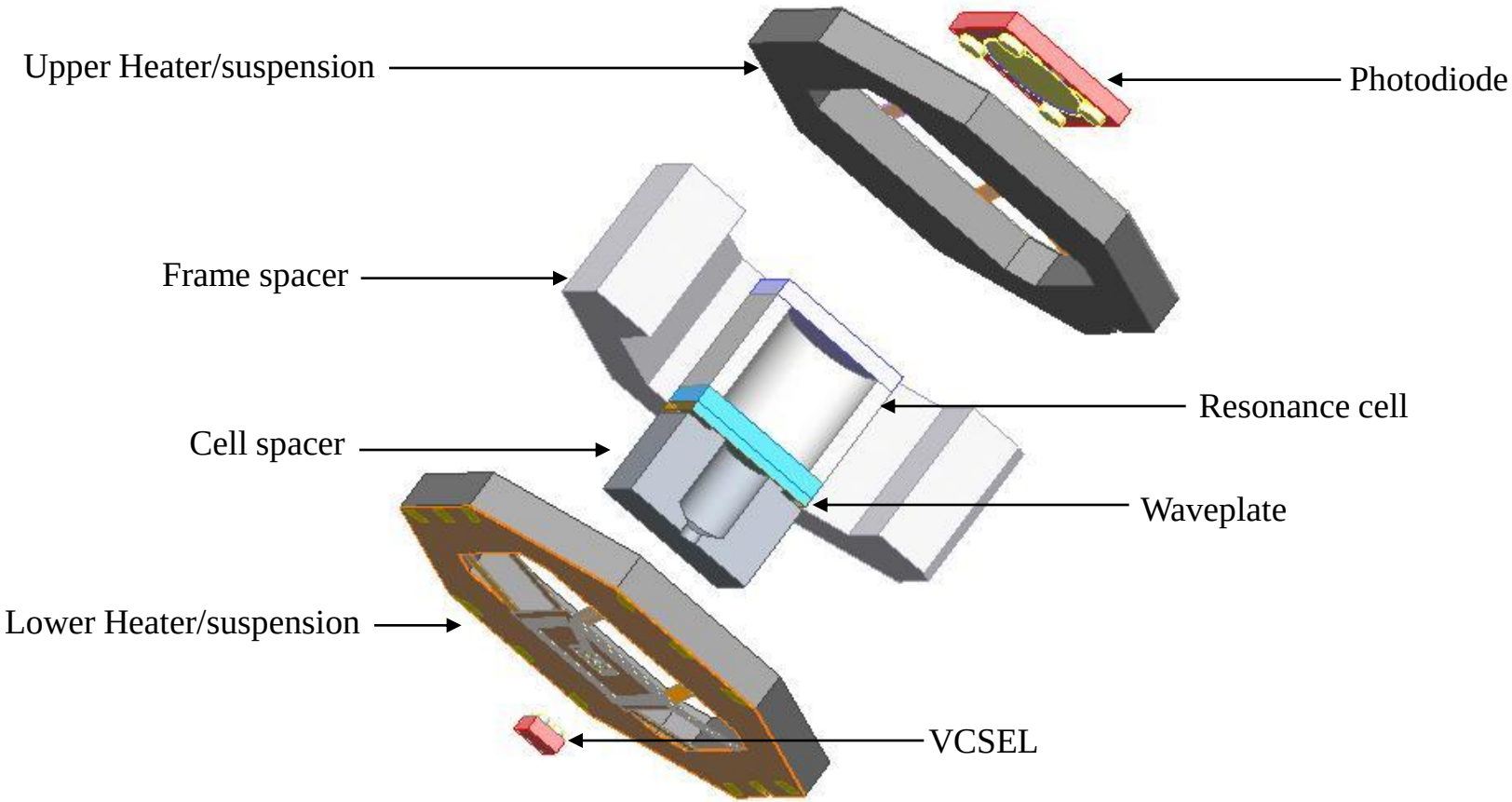
Gas	σ <SI> x 10^{-22} cm^2	D_0 cm^2/s.	β Hz/Torr	δ Hz/Torr °K	β/δ °K	RF signal arb-units
He	0.28±0.03[a]	0.20±0.04[a]	1185±46	1.49±0.15	795	1
Ne	0.93±0.09[a]	0.153±0.014[a]	---	---		1
Ar	10.4±1.0 [a]	0.134±0.02 [a]	-191.4±3[c]	-1.05±0.05[c]	182	0.5
Kr	255±36 [b]	0.138±0.03 [b]	-1450±50[c]	-1.9±0.5 [c]	763	0.15
N_2	6.0±0.4 [a]	0.087±0.015[a]	924.7±7	0.623±0.05	1484	1
CH_4	4.1±0.6	0.28±0.05	-1050±30	-1.47±0.09	714	1
C_2H_6	8.5±1.0	0.21±0.03	-1852±30	-1.87±0.02	990	1
C_3H_8	14.9±2.0	0.143±0.025	-2959±37	-2.03±0.08	1457	1
C_2H_4	59.5±6.0	0.174±0.034	---	---	---	---
C_4H_{10}	---	---	-3995	-2.0	1997	1

a - from ref. 7; b - from ref. 8; c - from ref. 10

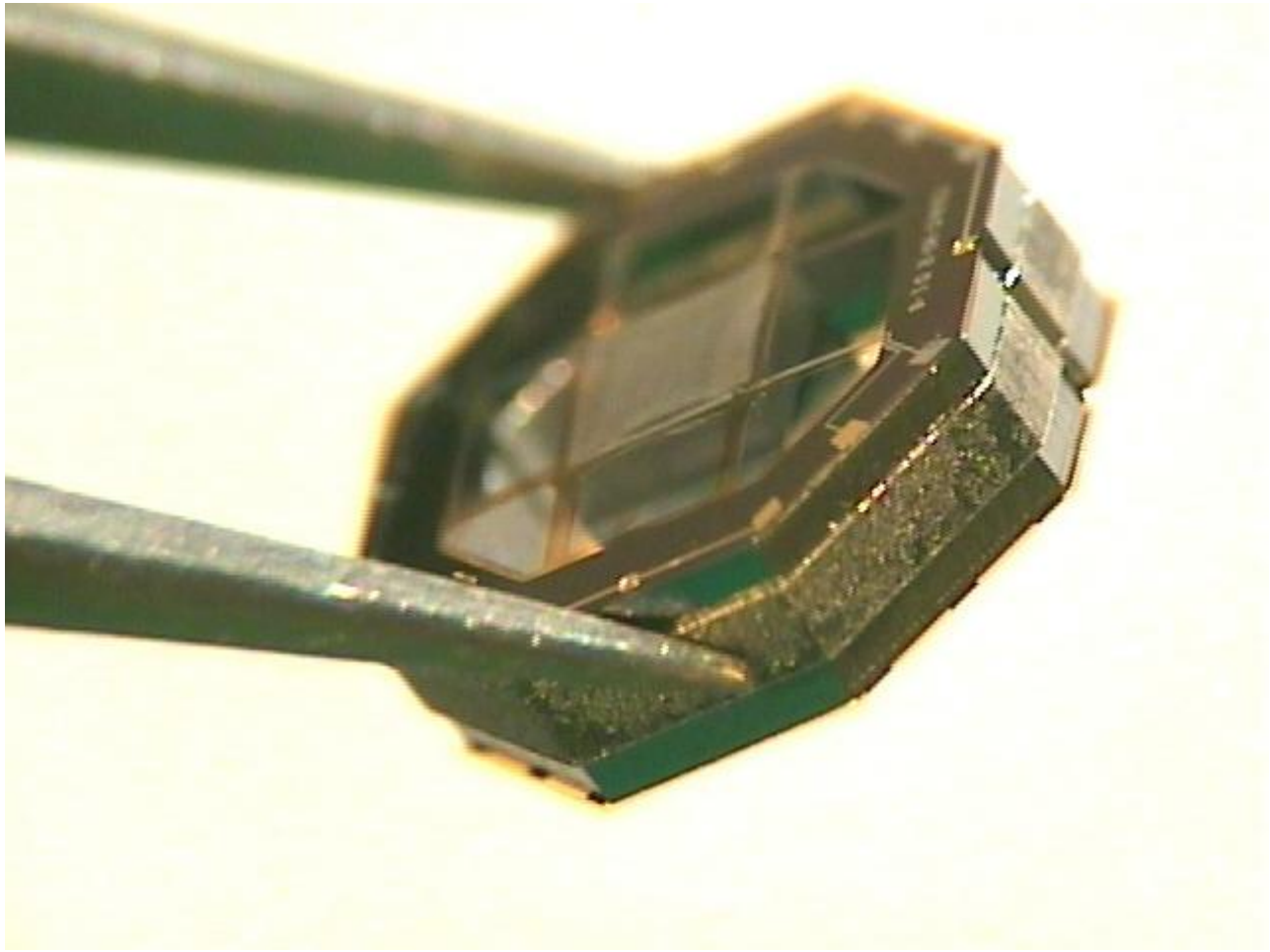
Cesium buffer gas shifts, from Strumia, et al., FCS 1976

See also Section 3.5 in J. Vanier and C. Audoin, *The Quantum Physics of Atomic Frequency Standards*

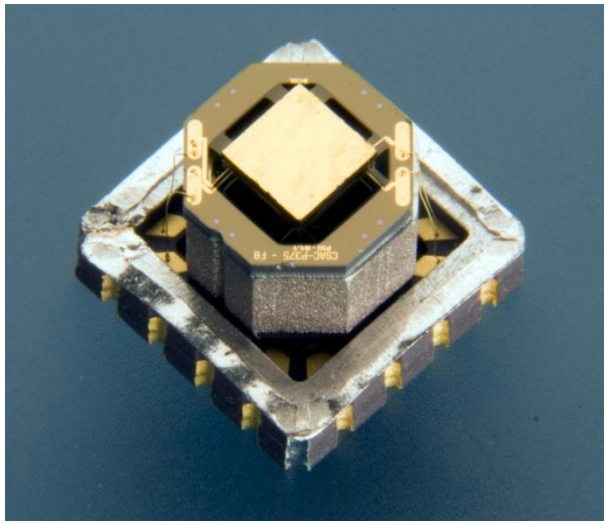
Physics Package Assembly



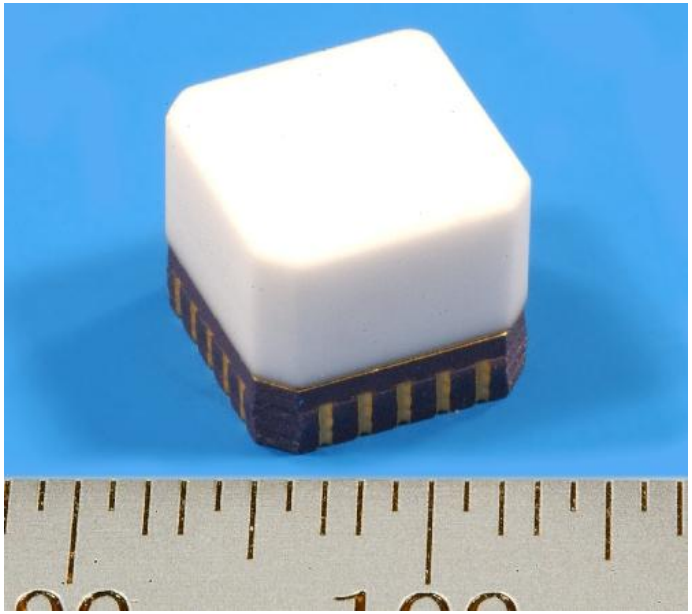
Physics Package



Physics Package in LCC

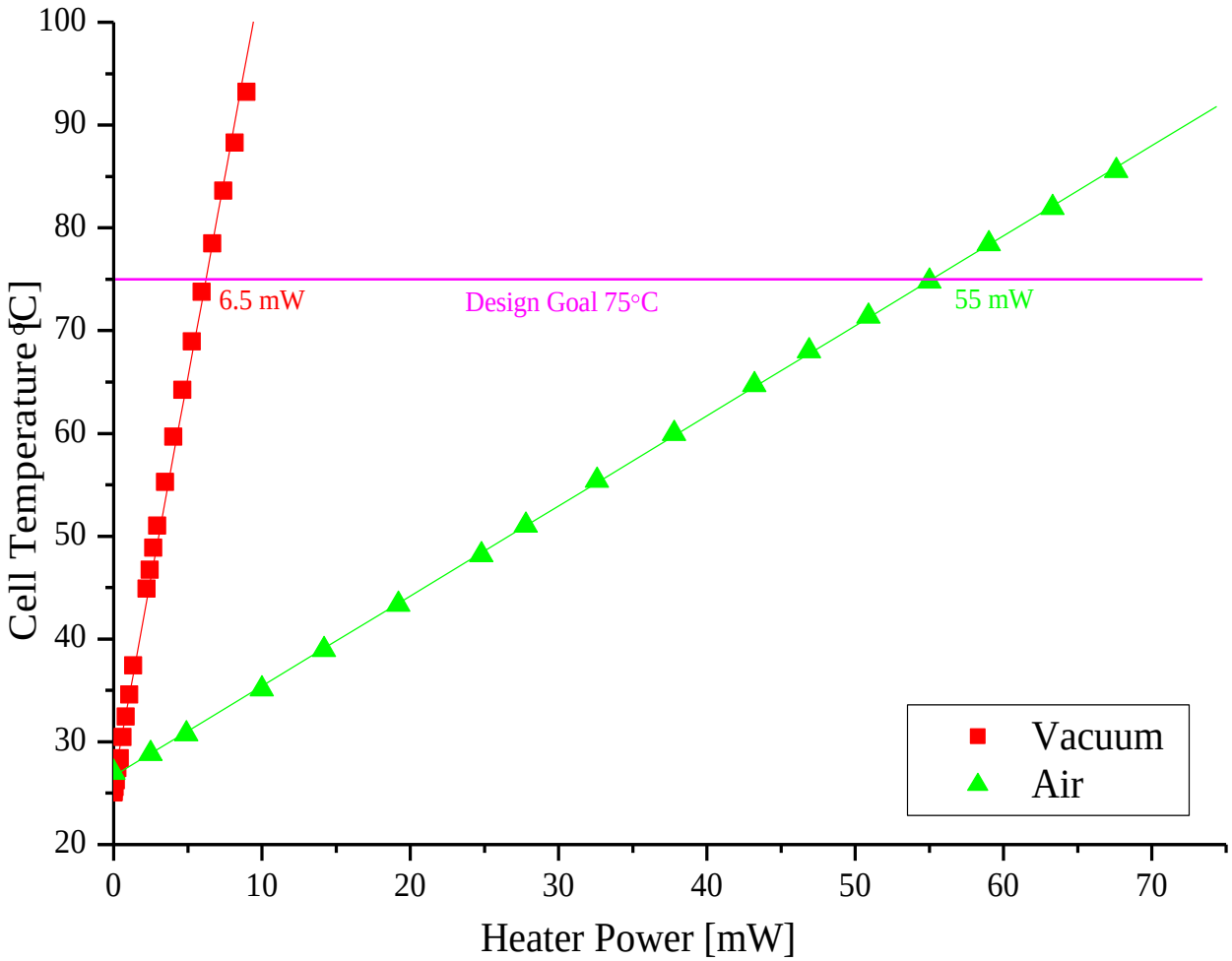


Physics package in LCC



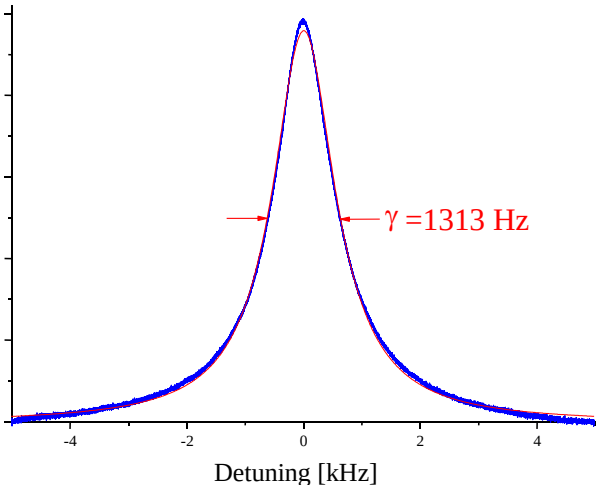
Vacuum-Sealed

Thermal Isolation



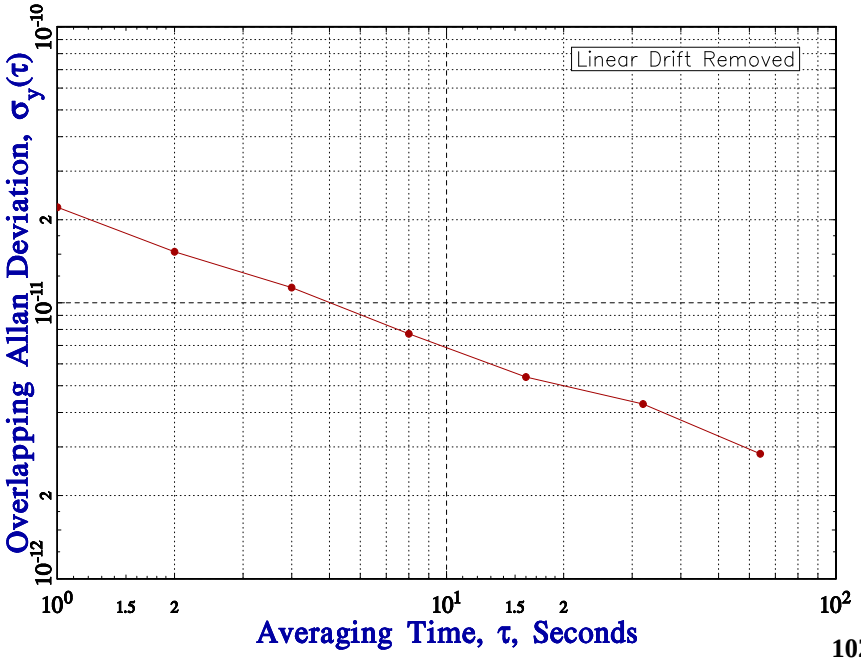
Physics Package Performance

PPIII CPT Resonance

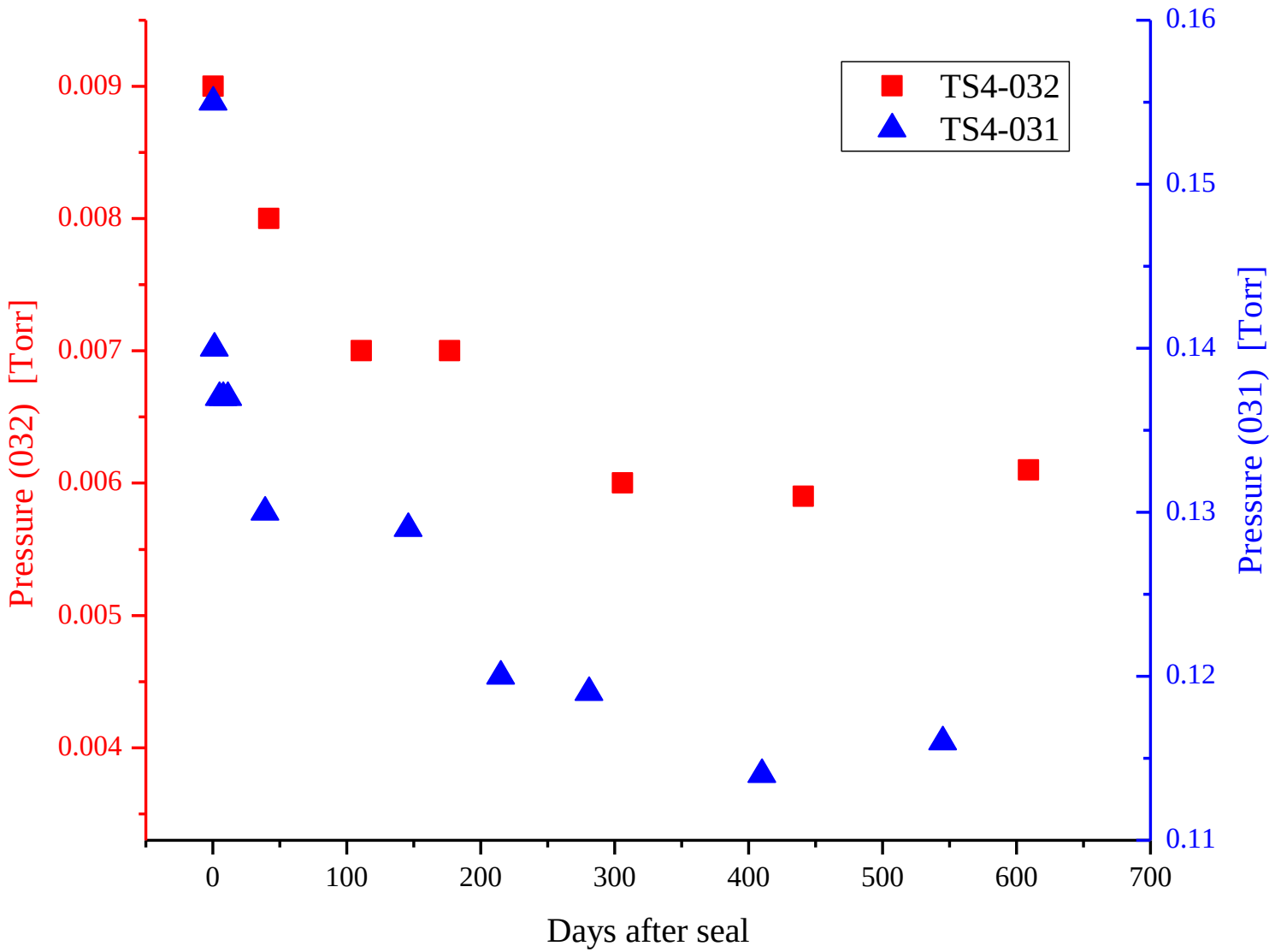


Resonance "Q" = 5×10^7

FREQUENCY STABILITY

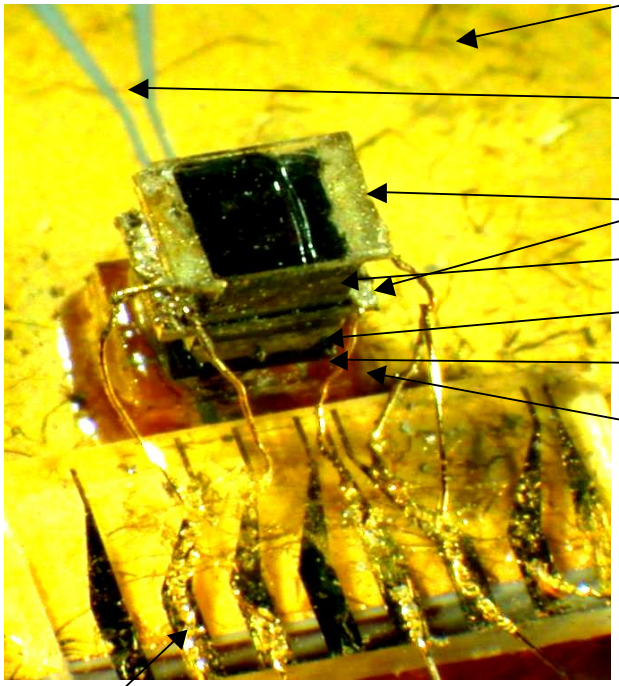


Vacuum Integrity ("Power aging")



Other CSAC Physics Packages

The NIST CSAC-1 Physics Package



Alumina substrate coated with gold

Current input for VCSEL

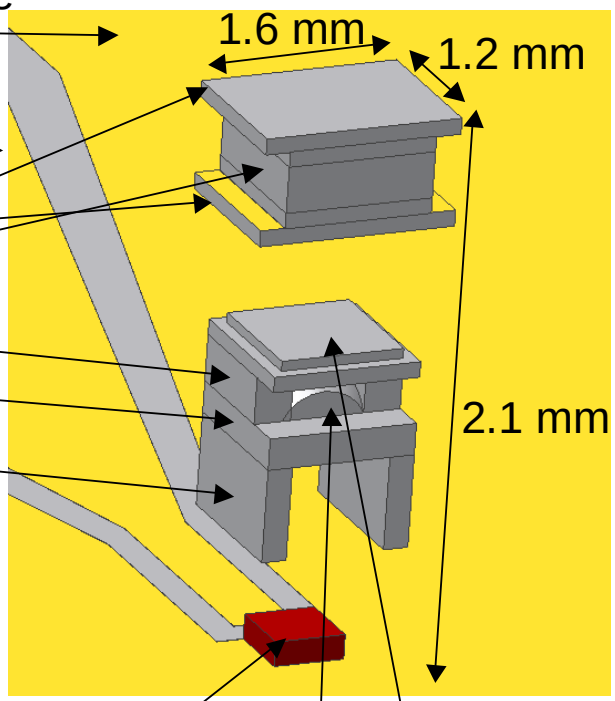
ITO heater

Cell

Lens spacer

ND filter

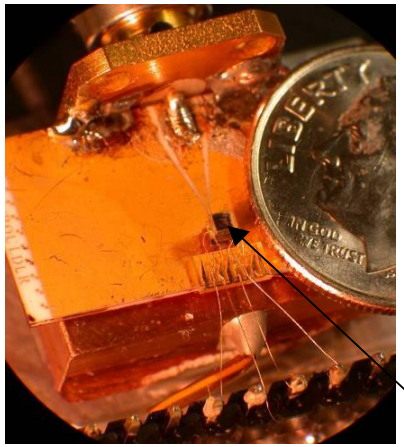
Vespel spacer



VCSEL Lens Waveplate

Glass substrate with gold traces for connections to ITO heaters and photo diode

We have not yet mounted a photo diode on the top.



CSAC with a dime

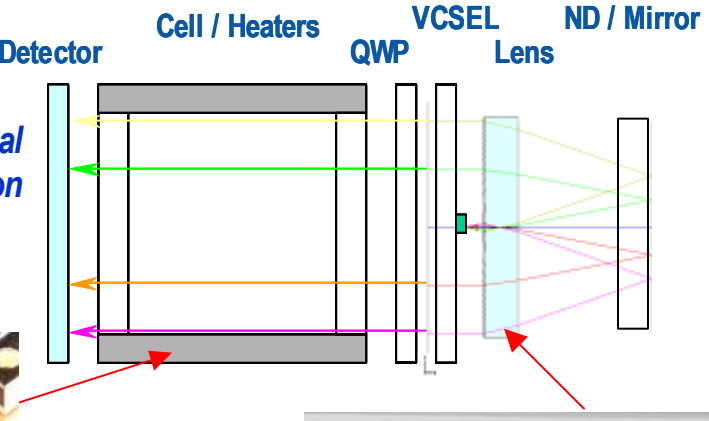
- Total volume: 4.0 mm^3
- Wafer-level assembly possible

This is a picture of the first NIST CSAC PP that first operated on Nov. 26, 2003

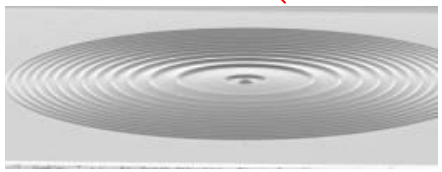
Phase-III Physics Package
driving towards 1cc, 30mW CSAC

- Novel dual-pass optical configuration for reduced size, power
- Custom microfabricated optics for compact size, batch fabrication
- Compact, tube-free vapor cell for small size, high manufacturability

Dual-pass optical configuration

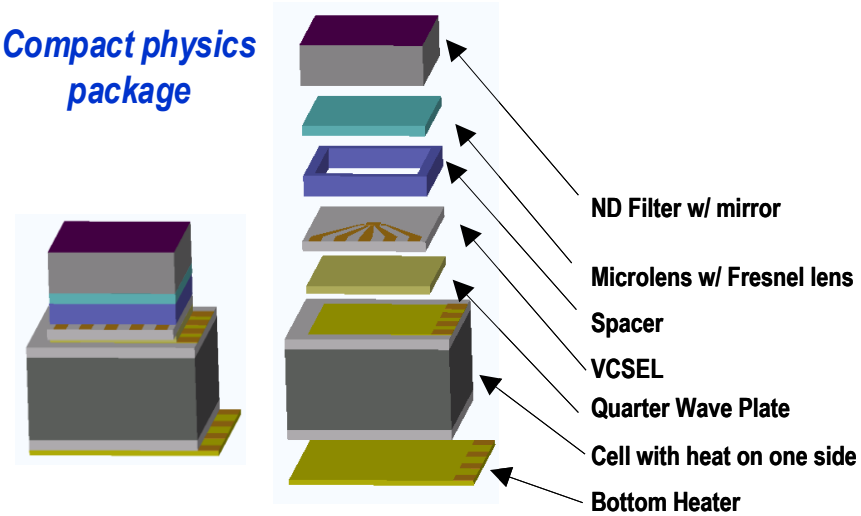


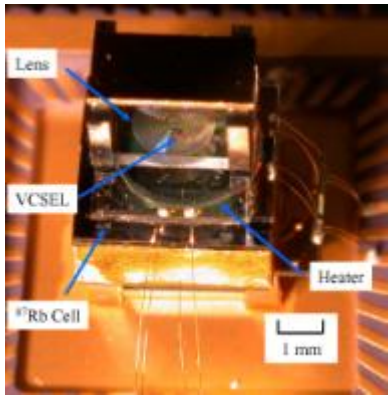
Compact Vapor Cells



Microfabricated Optics

Compact physics package





Phase-III Physics Package

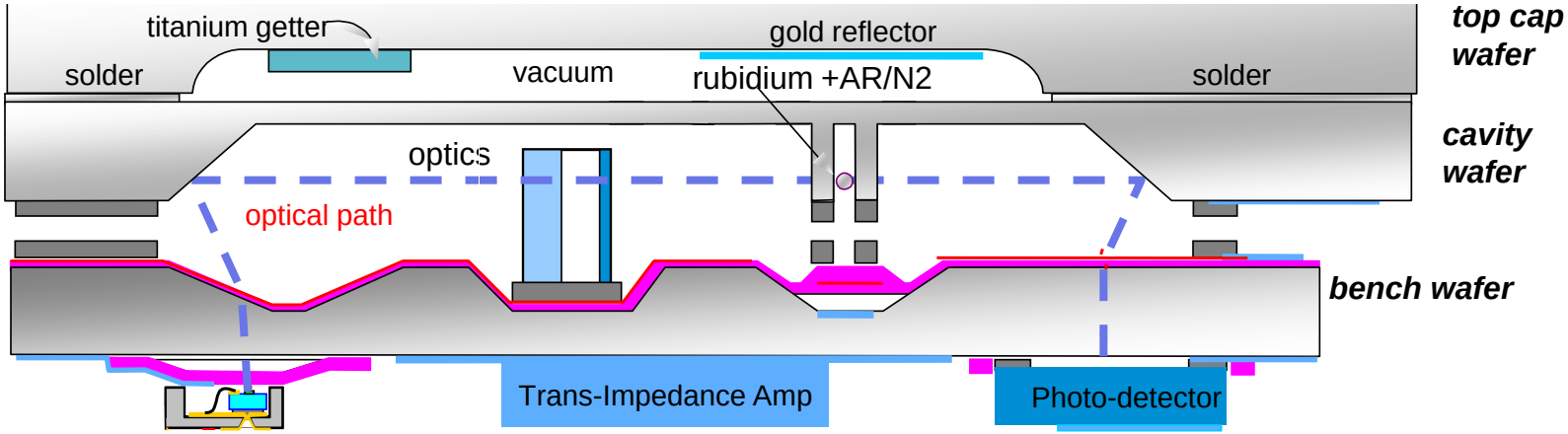
reduce size, power and improve robustness / assembly

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologies Company

Agilent Technologies

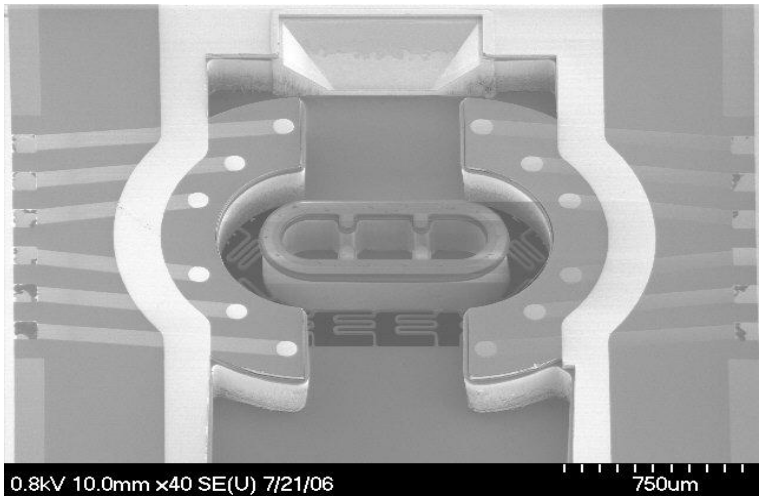
Rockwell Collins

Slide courtesy of Jeff DeNatale, Teledyne

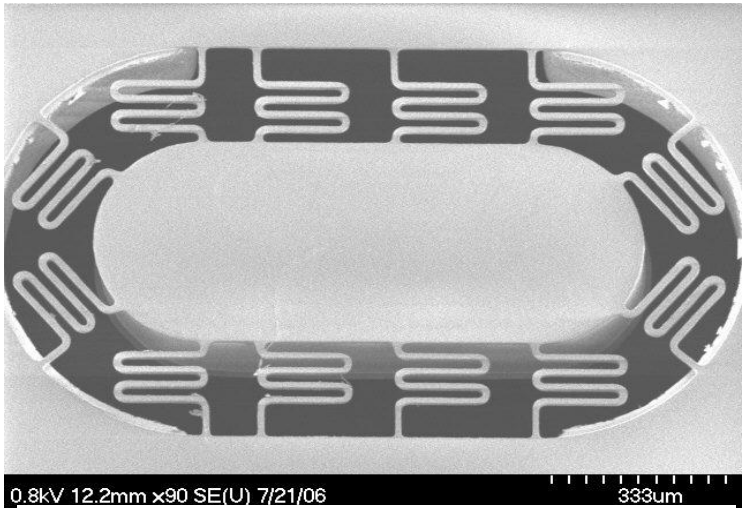


3 wafer stack

Batch fabrication for reduced assembly cost



87Rb cavity: front



87Rb cavity: back

Slide courtesy of Dan Youngner, Honeywell

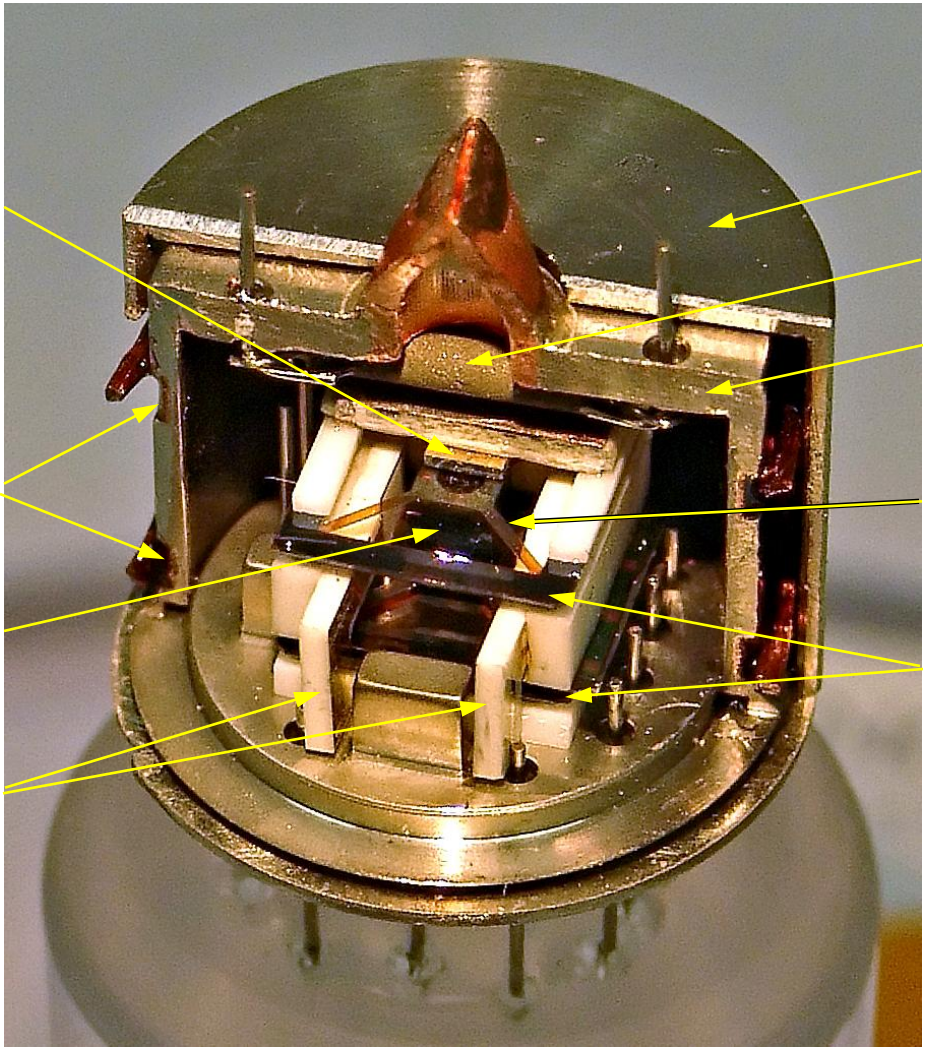
Sarnoff End-State CSAC

Photo-detector

Z-axis magnetic bias-field coils

MEMS cesium vapor-cell

RF-drive input



8 mm scale

Magnetic shielding

Vacuum "getter"

Vacuum package

MEMS Structures:

- Thermally isolating support
- Integrated heaters
- Integrated temp sensors
- Three such structures/CSAC:
  - VCSEL laser support
  - Bottom of cesium cell
  - Top of cesium cell

Characteristics:

- CW VCSEL
- Direct RF Interrogation
- ~20 mW DC Power
- sub-mW RF Power

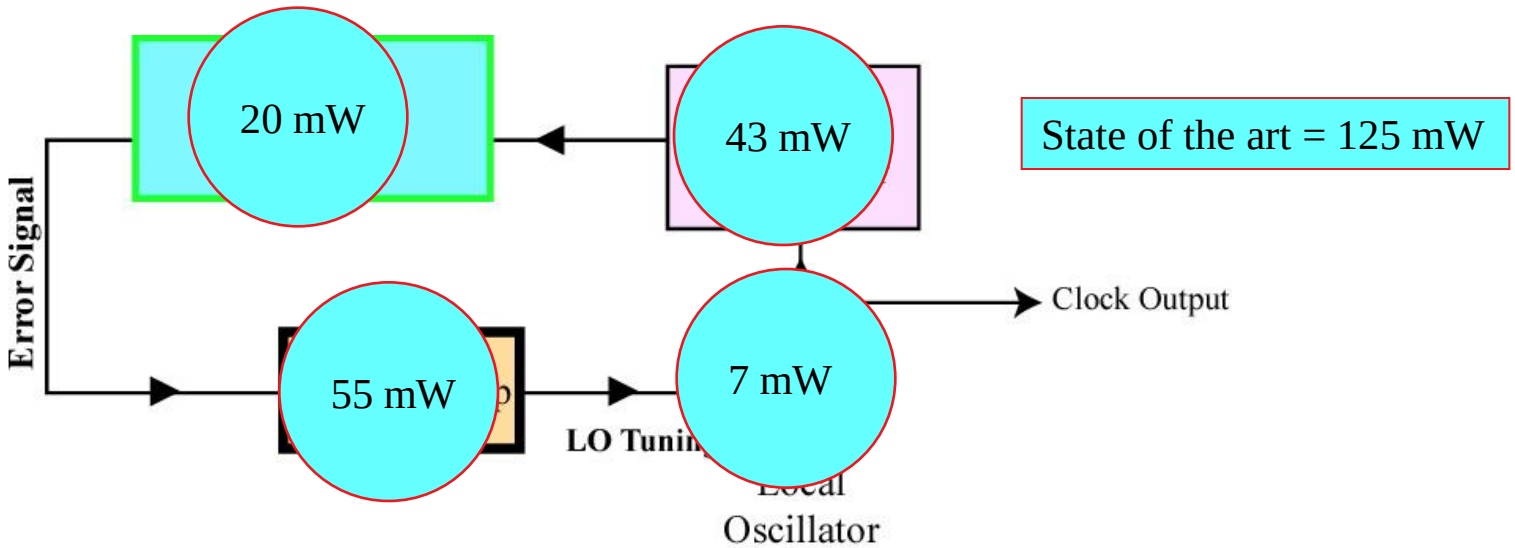
SARNOFF Corporation

Inventing the Future!

Slide courtesy of Alan Braun, Sarnoff

Electronics

The Big Picture

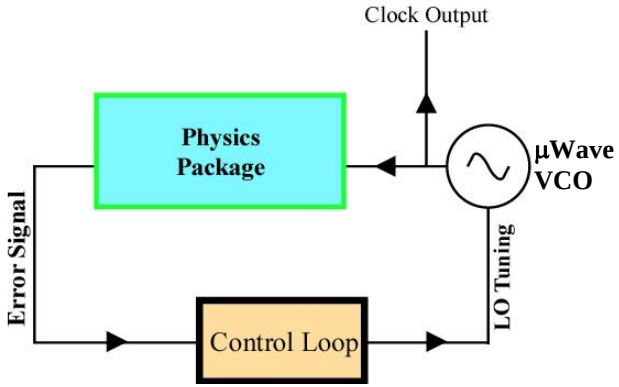


- 30 mW prototype CSACs have been demonstrated
- "Fully-Functional" CSACs typically 100-200mW
  - Symmetricom SA.45s CSAC is 125 mW
- Physics package is actually the lowest power of key systems
- Big gains should be possible in Microwave Synthesis and Control Circuits.

Microwaves

Two Approaches to Microwaves

Stable μWave Oscillator locked directly to physics



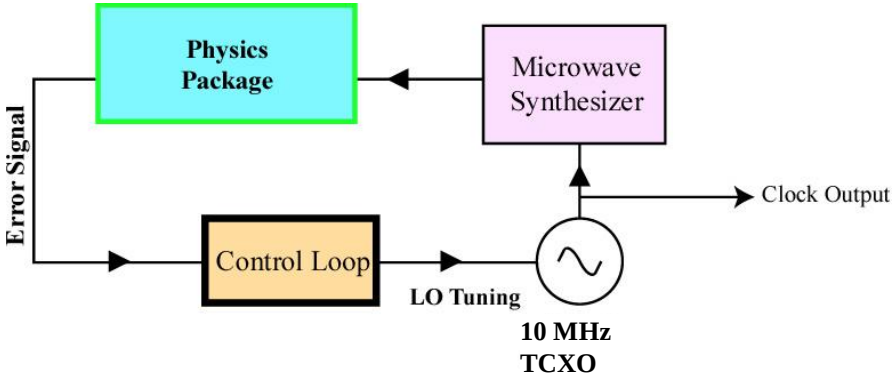
Pros:

- Simple, low parts count
- Low power

Cons:

- Microwave output frequency
- μWave Oscillator must have adequate phase noise
- Output frequency cannot be calibrated
- Interrogation modulation appears on output

Digitally-controlled synthesizer referenced to RF TCXO which is locked to physics



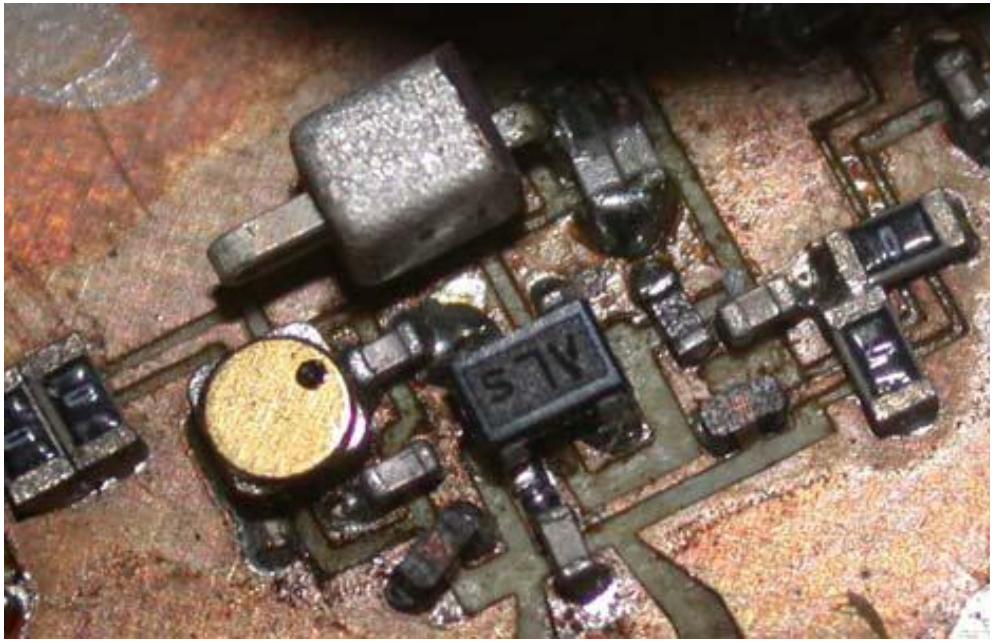
Pros:

- Digital control
- 10.0 MHz calibrated output
- Spectrally-pure output signal

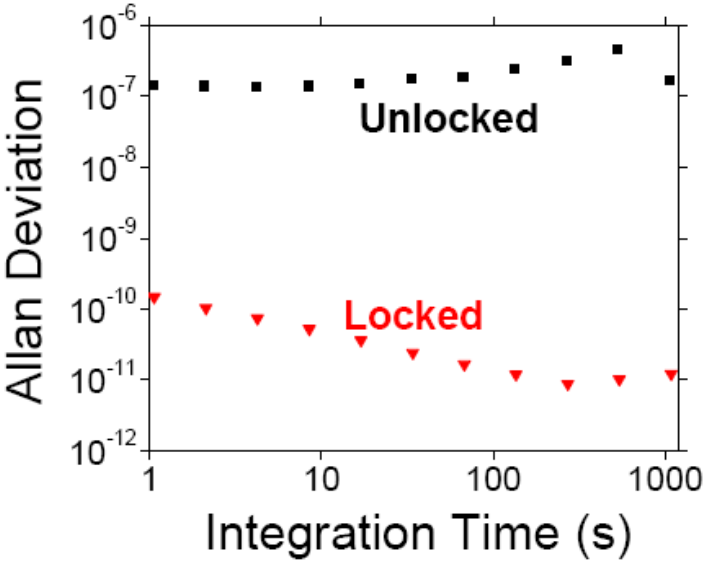
Cons:

- High power
- High complexity/parts count

NIST/CU Coaxial Resonator Oscillator



From: Gerginov, et. al., FCS 2005

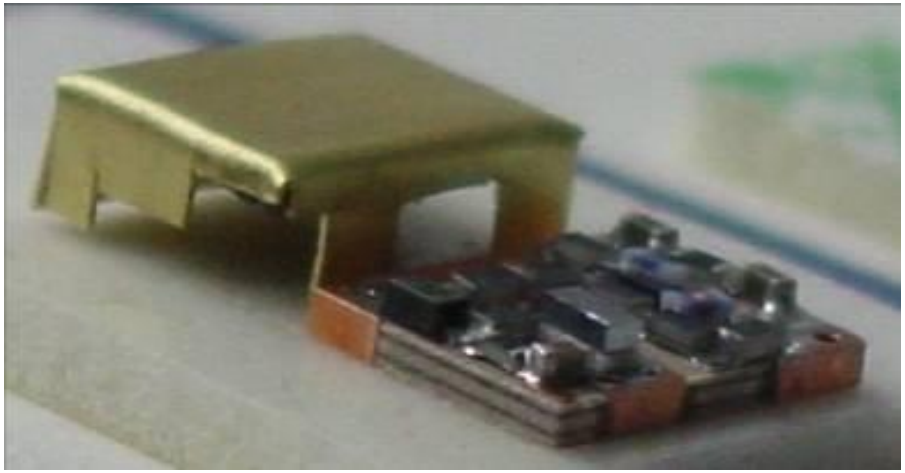


From: Gerginov, et. al., FCS 2005

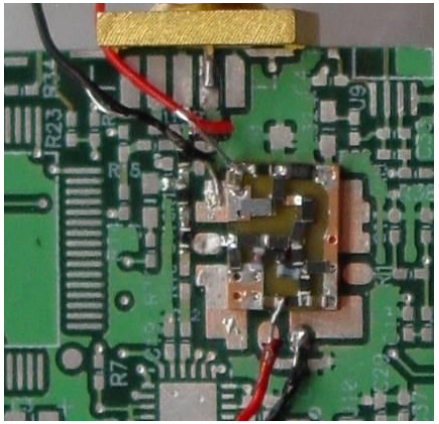
Resonator Q ≈ 250
DC Power = 2.5 mW
Output Power = -6 dBm
Phase Noise = -33 dBc @ 100 Hz

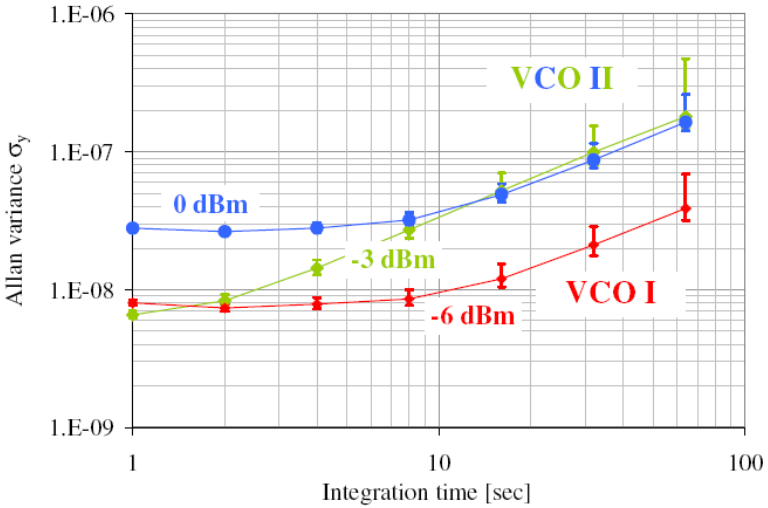
See also A. Brannon, et. al., "A low-power, low phase noise local oscillator for chip-scale atomic clocks," 2005 IEEE MTT-S International Microwave Symposium Digest, vol. 12-17, pp. 1535-1538, June 2005.

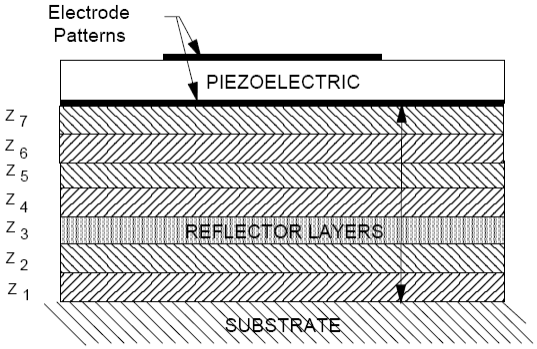
Spectral Research TFR-Oscaillator



Resonator Q ≈ 400
DC Power = 7.6 mW
Output Power = -3 dBm
Phase Noise = -53 dBc @ 300 Hz
σ_y(1 sec) = 6.5 x 10^{-9}







Thin-Film Resonator (TFR)
Lakin, et al, FCS 2003

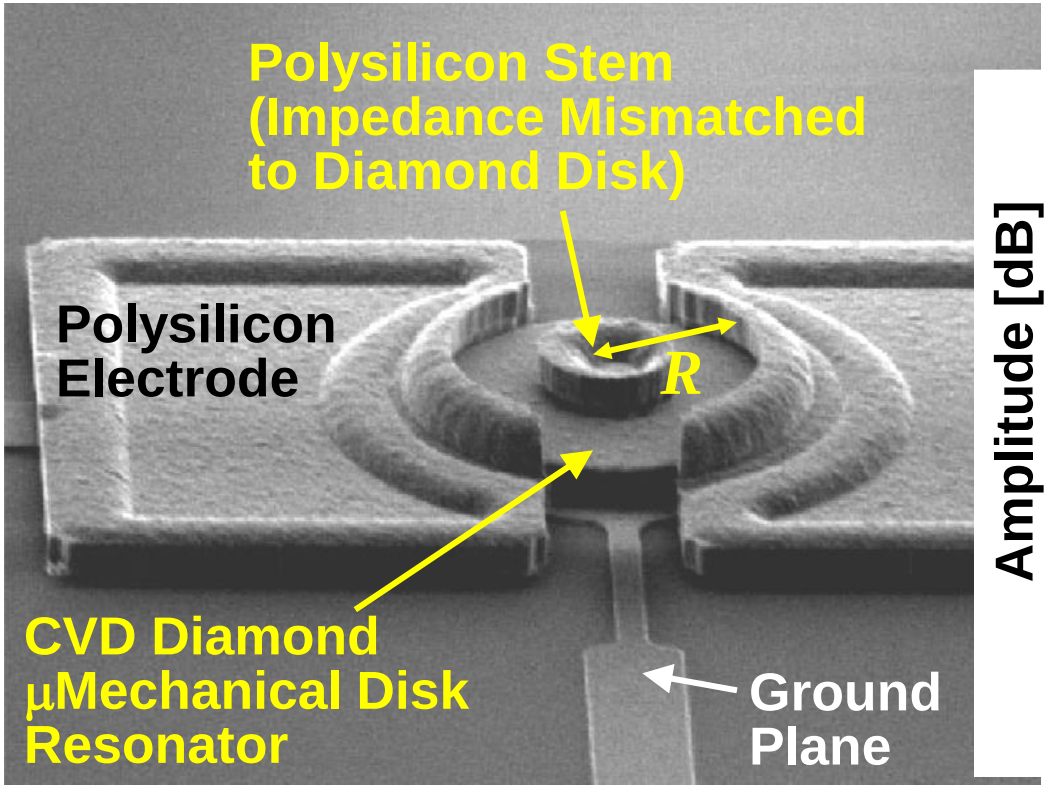
Spectral Research

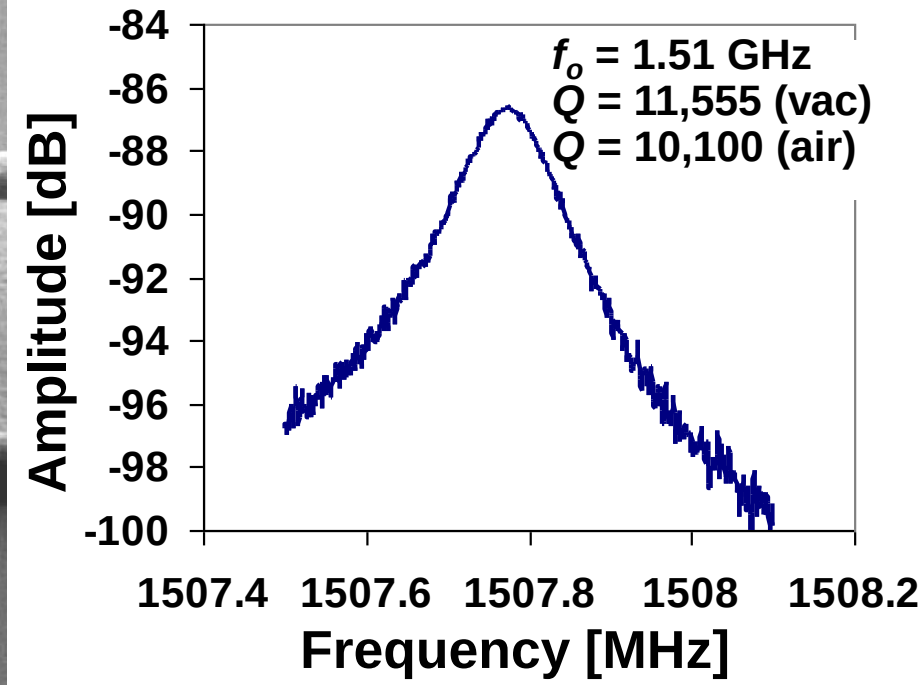
S.Romisch and R.Lutwak "Low-power, 4.6-GHz, stable oscillator for CSAC ," *FCS 2006*

MEMs Resonators

Symmetricom

Design/Performance:
R=10μm, ***t***=2.2μm, ***d***=800Å, V_P=7V
f_o=1.51 GHz (2nd mode), ***Q***=11,555

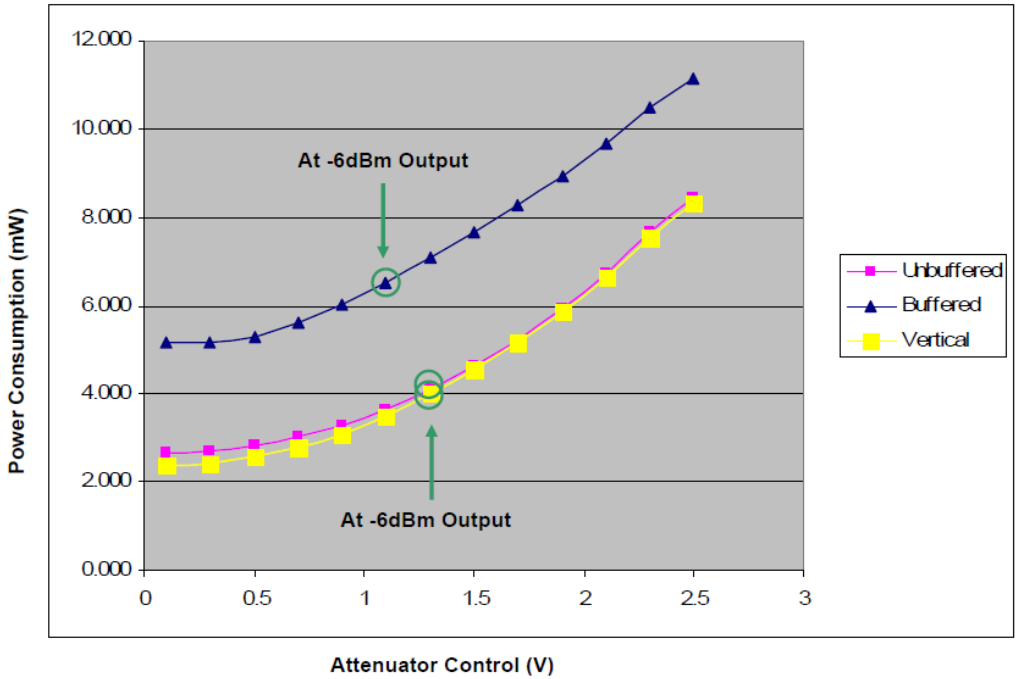


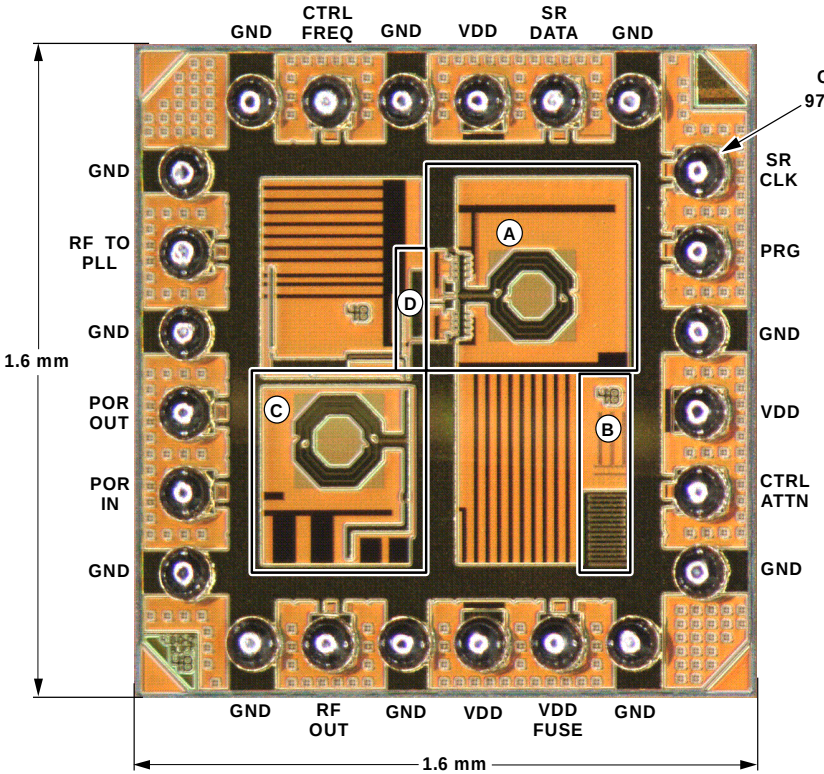


Extraordinary Q but not yet up to high enough frequencies for CSAC

Figure from: C.Nguyen and J.Kitching, "Towards Chip-Scale Atomic Clocks," *Proc. ISSCC*, 2005

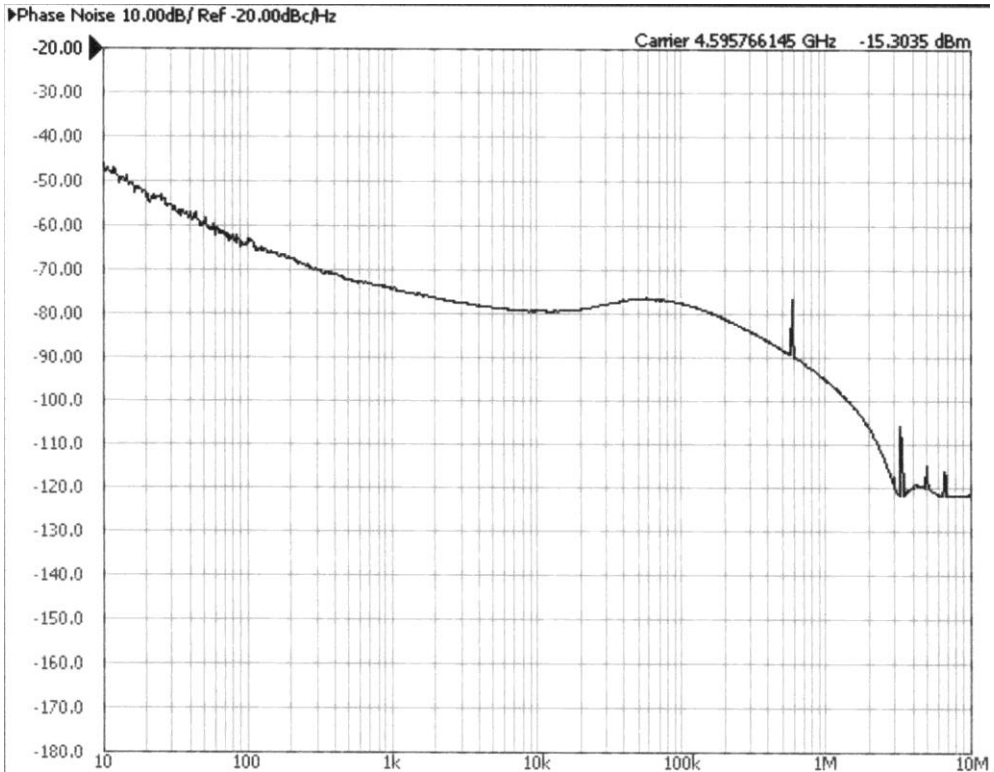
Mayo Clinic Microwave VCO

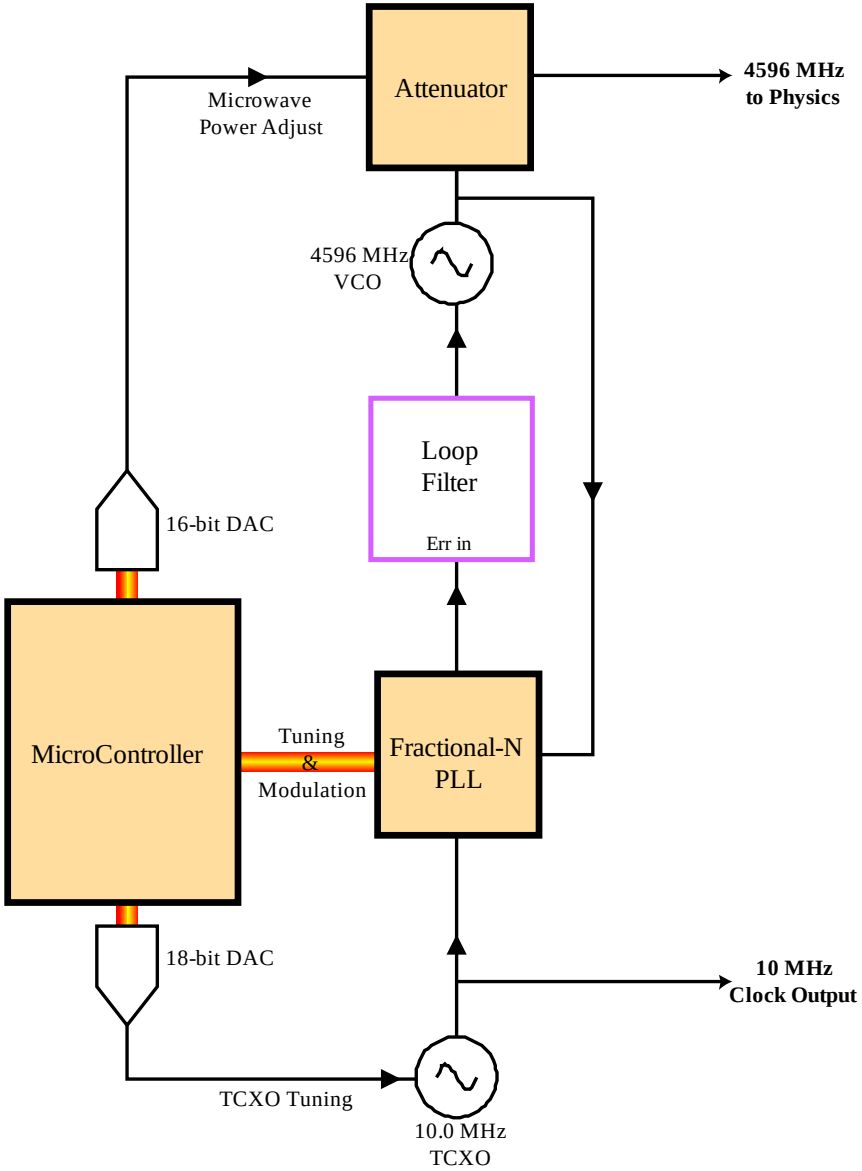




Symmetricom SA.45s Synthesizer

- Modulation via digital control of PLL
- Tuning via digital control of PLL Resolution: $2x10^{-12}$
- Output is 10.0 MHz
- Power adjust 0 to -10 dBm
- Good phase noise (-75 dBc @ 1 kHz)
- Relatively High Power (≈ 50 mW)



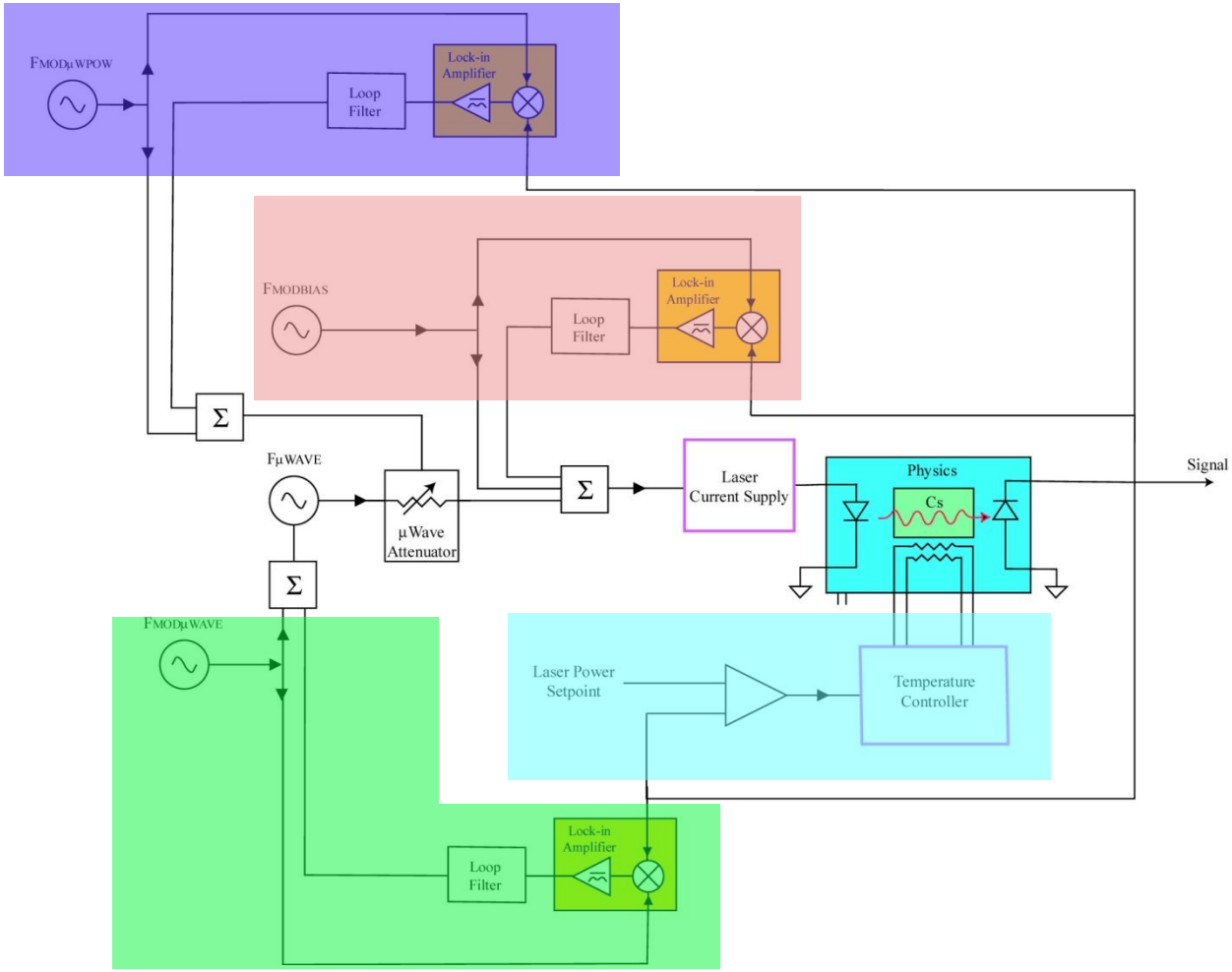


Control Systems

Control System Requirements

- Provide low-noise control signals
  - TempSet (Cell and/or VCSEL heaters)
  - Microwave synthesizer (tuning and power adjust)
  - VCSEL Current
- Low-noise signal processing
  - Amplification/digitization of signal
- Turn-on acquisition
  - Autonomous acquisition of optimum control parameters
  - May be mix of memorized device-specific parameters and empirical acquisition.
- Operation
  - Laser lock servo, Laser power servo, clock servo, microwave power servo
- Alarms/Monitoring/Failure Recovery
- Remote Control/Monitor via RS232

Control System



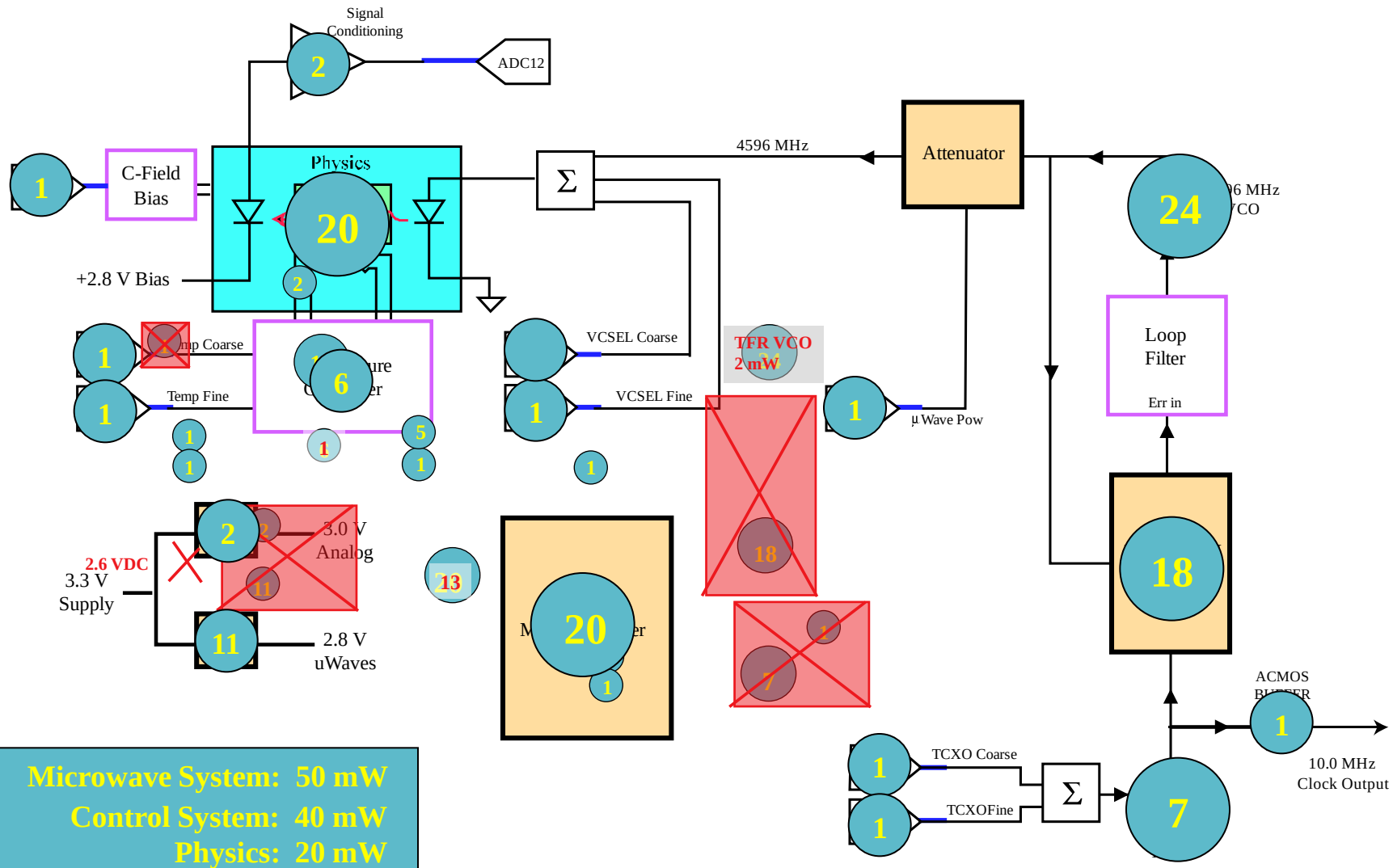
Laser Servo - Lock laser wavelength to optical absorption resonance via DC Bias

Temperature Servo - Optimize optical power via temperature

Clock Servo – Lock local oscillator to CPT resonance

Power Servo - Optimize CPT signal amplitude via μWave power

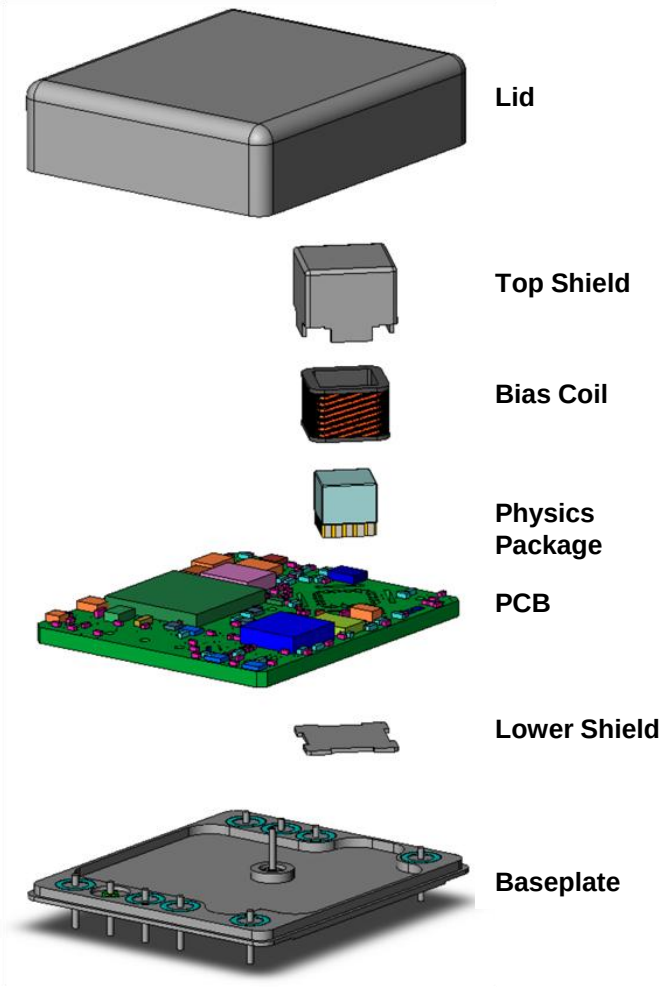
Symmetricom CSAC Block Diagram



Microwave System: 50 mW
Control System: 40 mW
Physics: 20 mW
Regulators & Passives: 15 mW

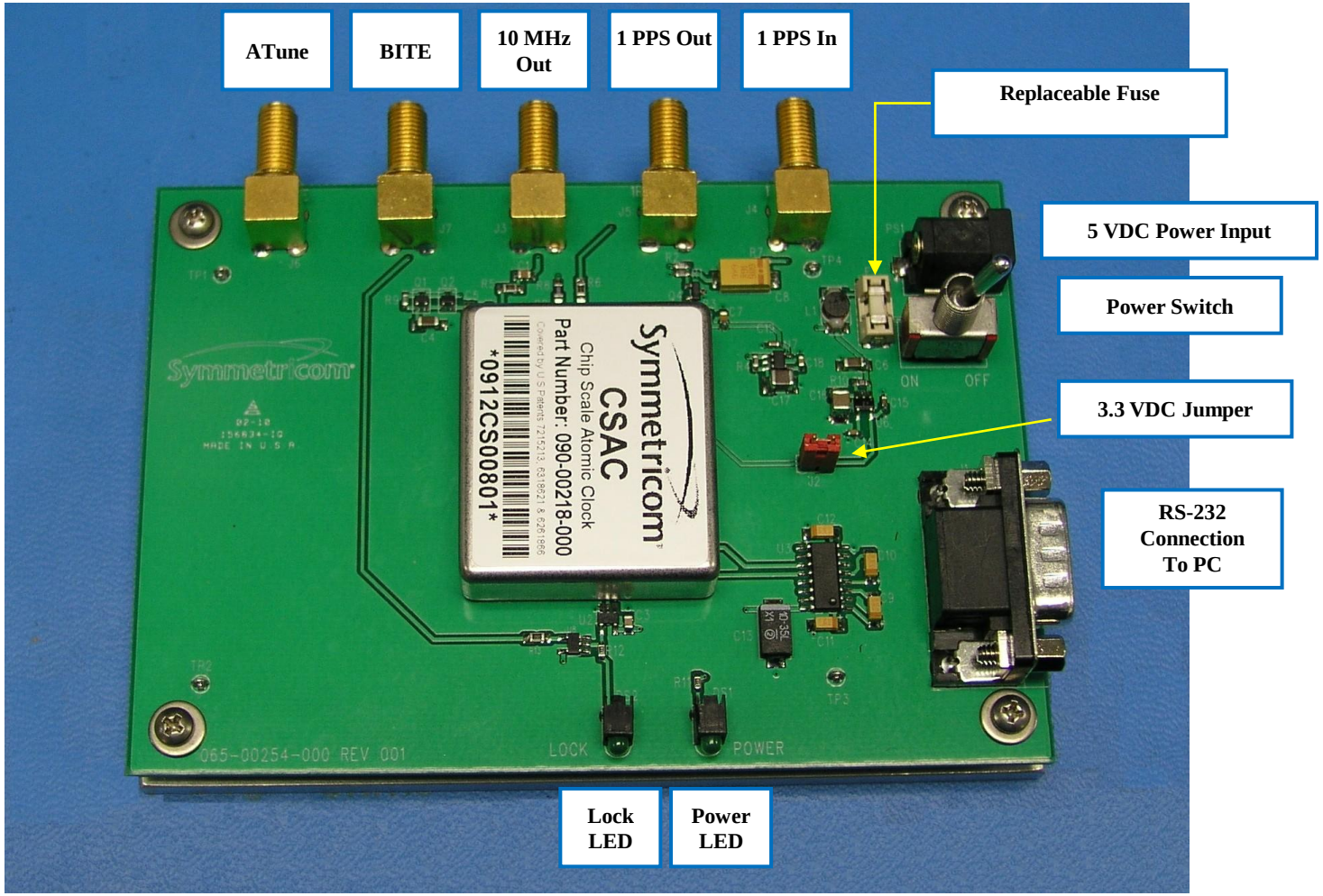
Total: 125 mW

SA.45s Chip-Scale Atomic Clock

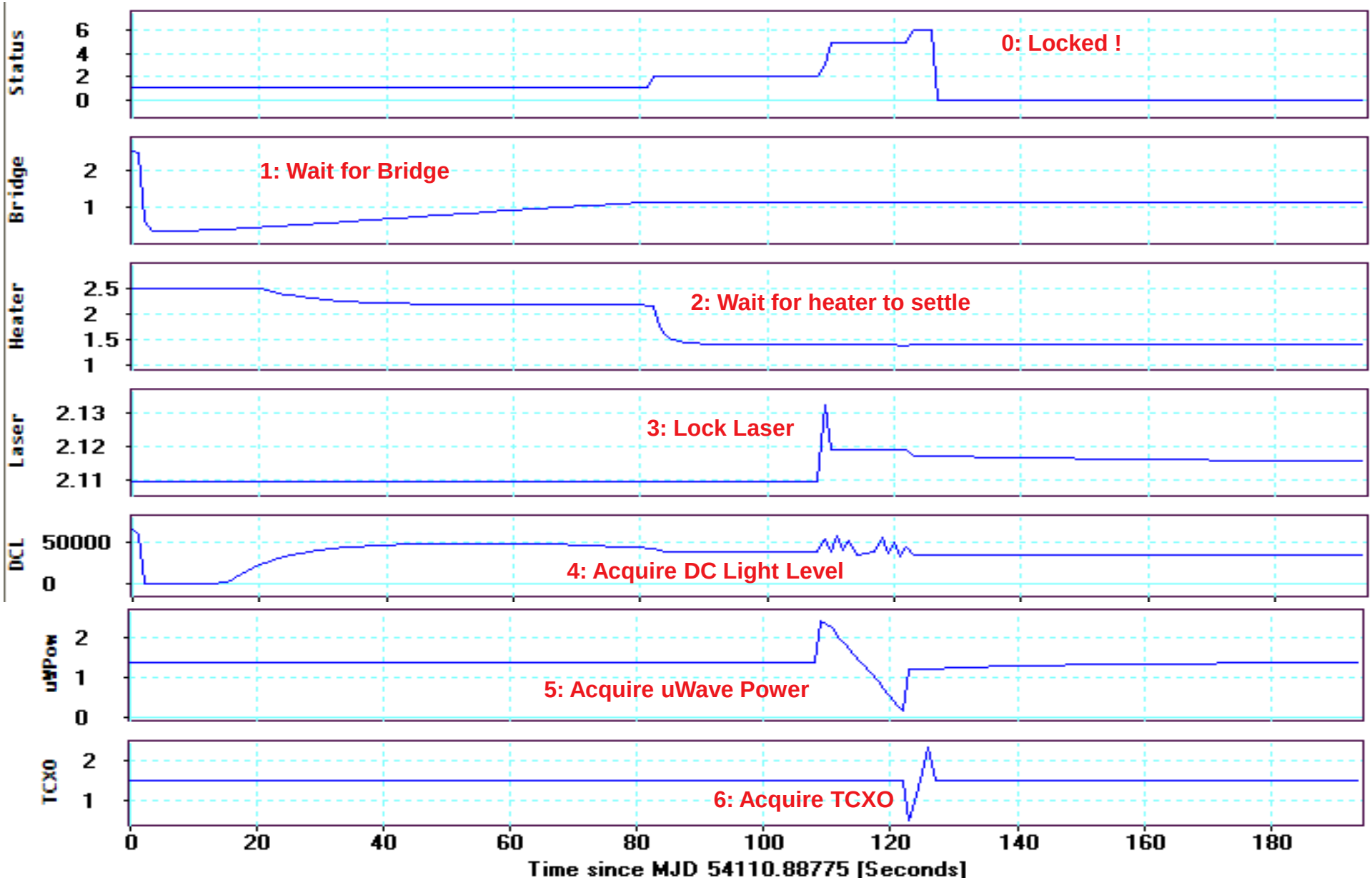


Laser welded seam

SA.45s CSAC on Evaluation Board

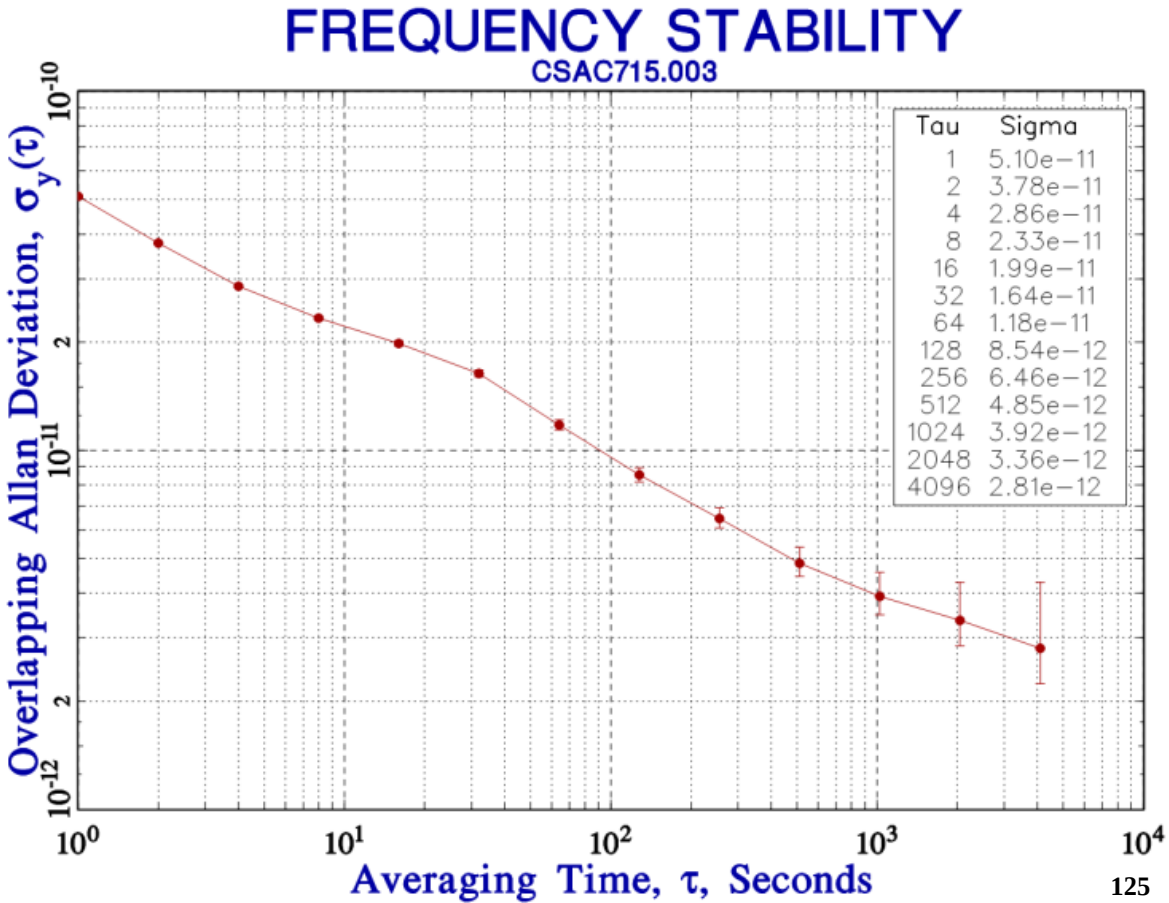


Acquisition

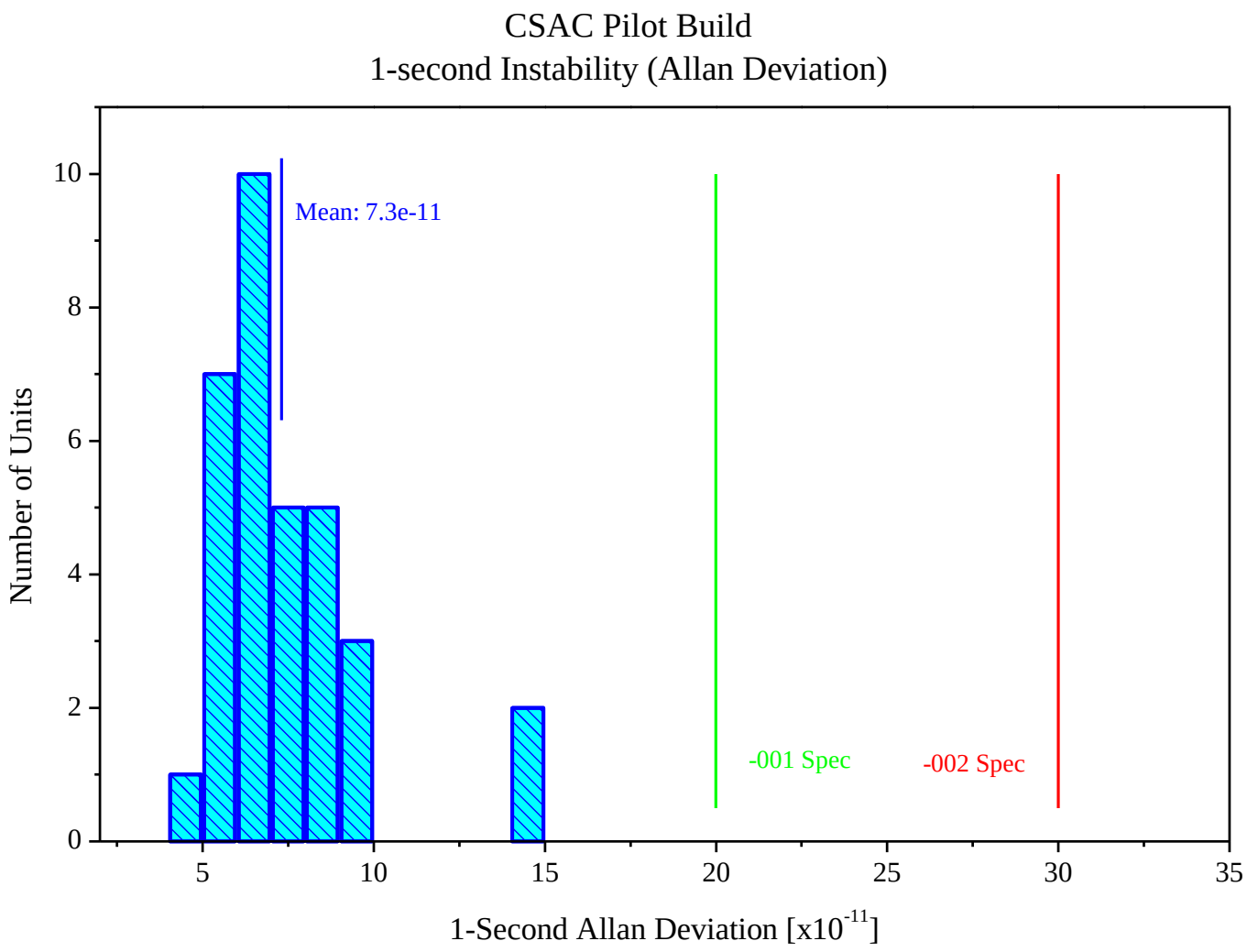


SA.45s CSAC Typical Performance

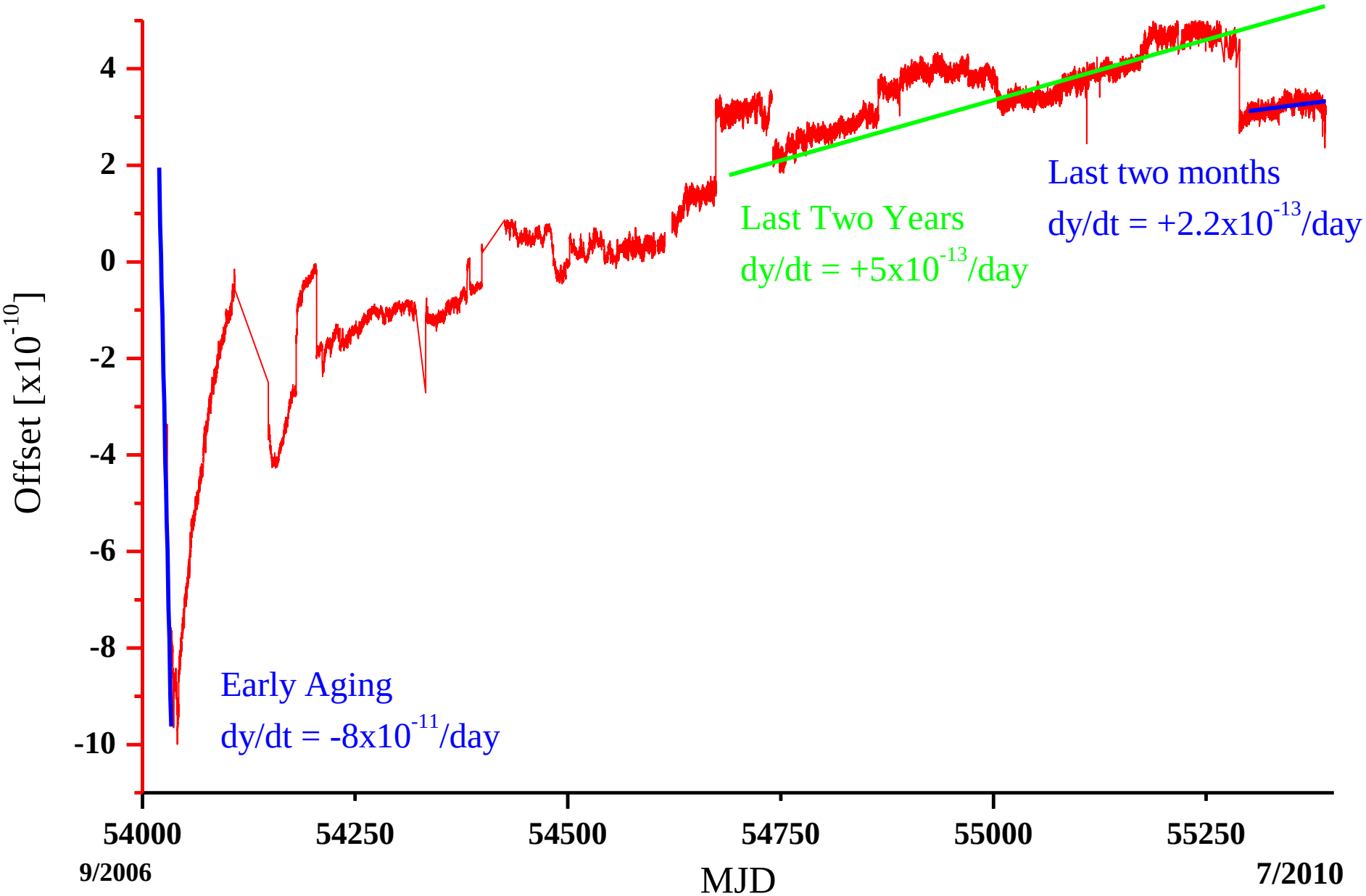
Size ≈ 15 cm^3
Power ≈ 125 mW
Stability ≈ 2-3 $x10^{-10}\ \tau^{-1/2}$



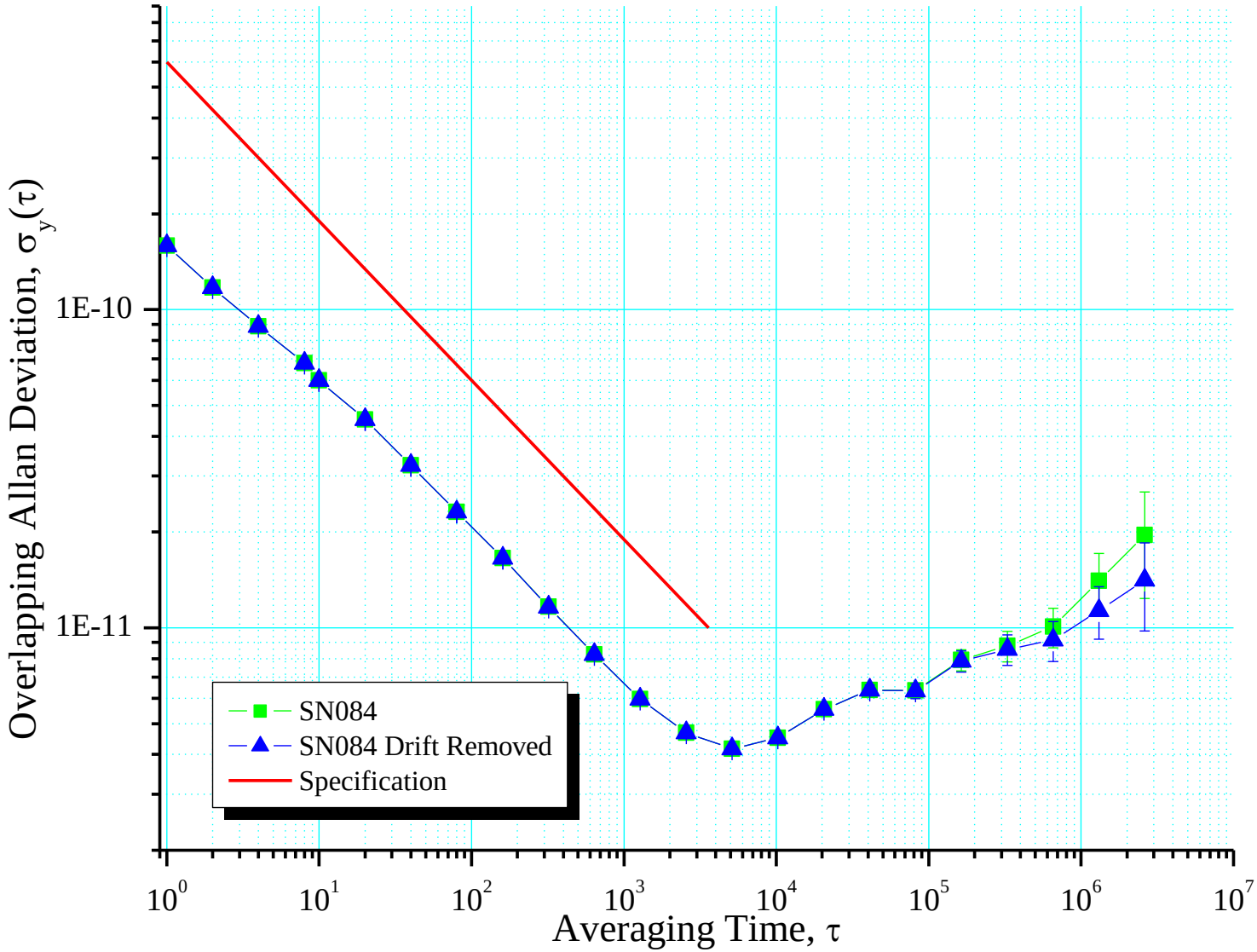
SA.45s Pilot Unit ADEV



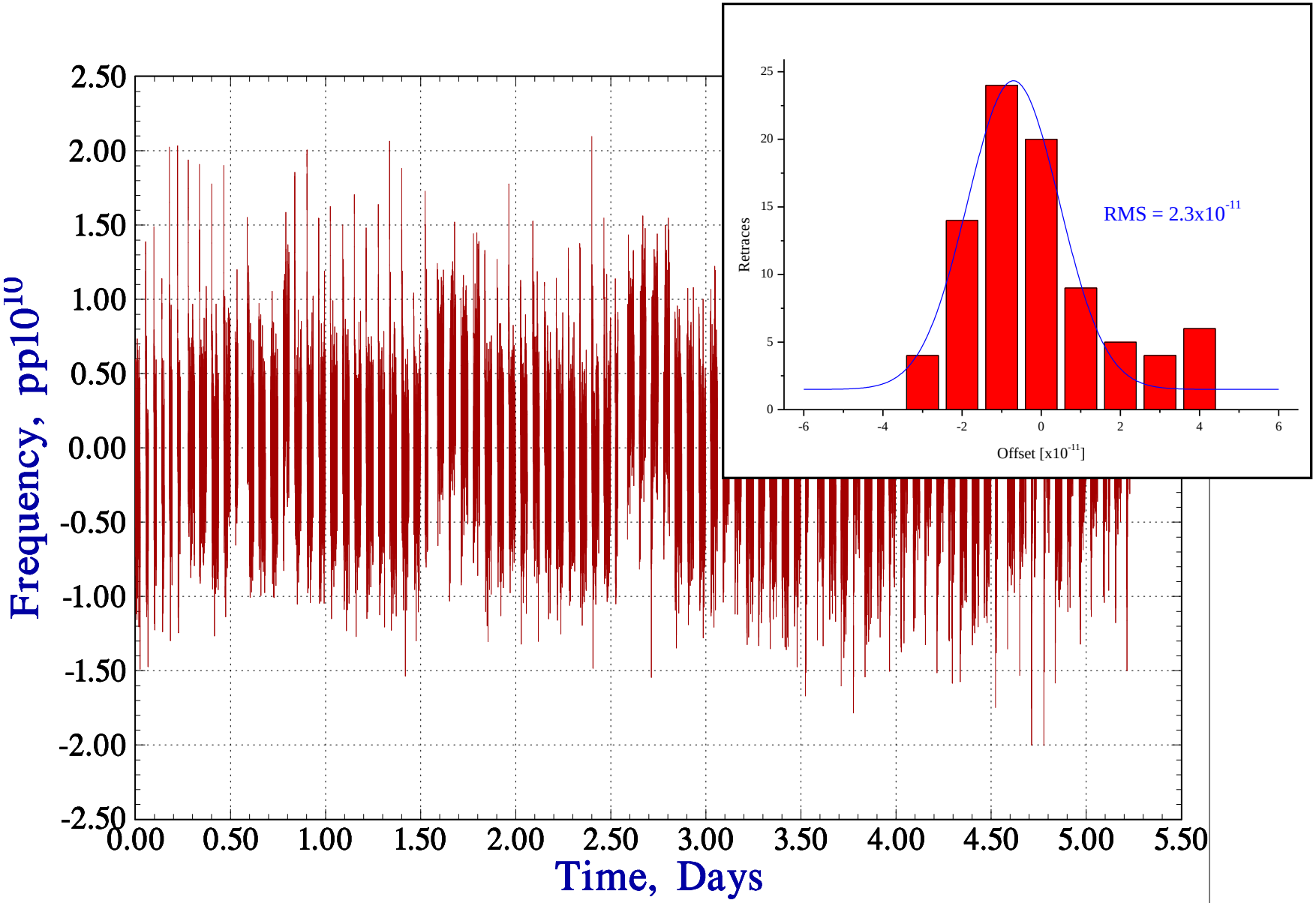
Long-term aging (SN084)



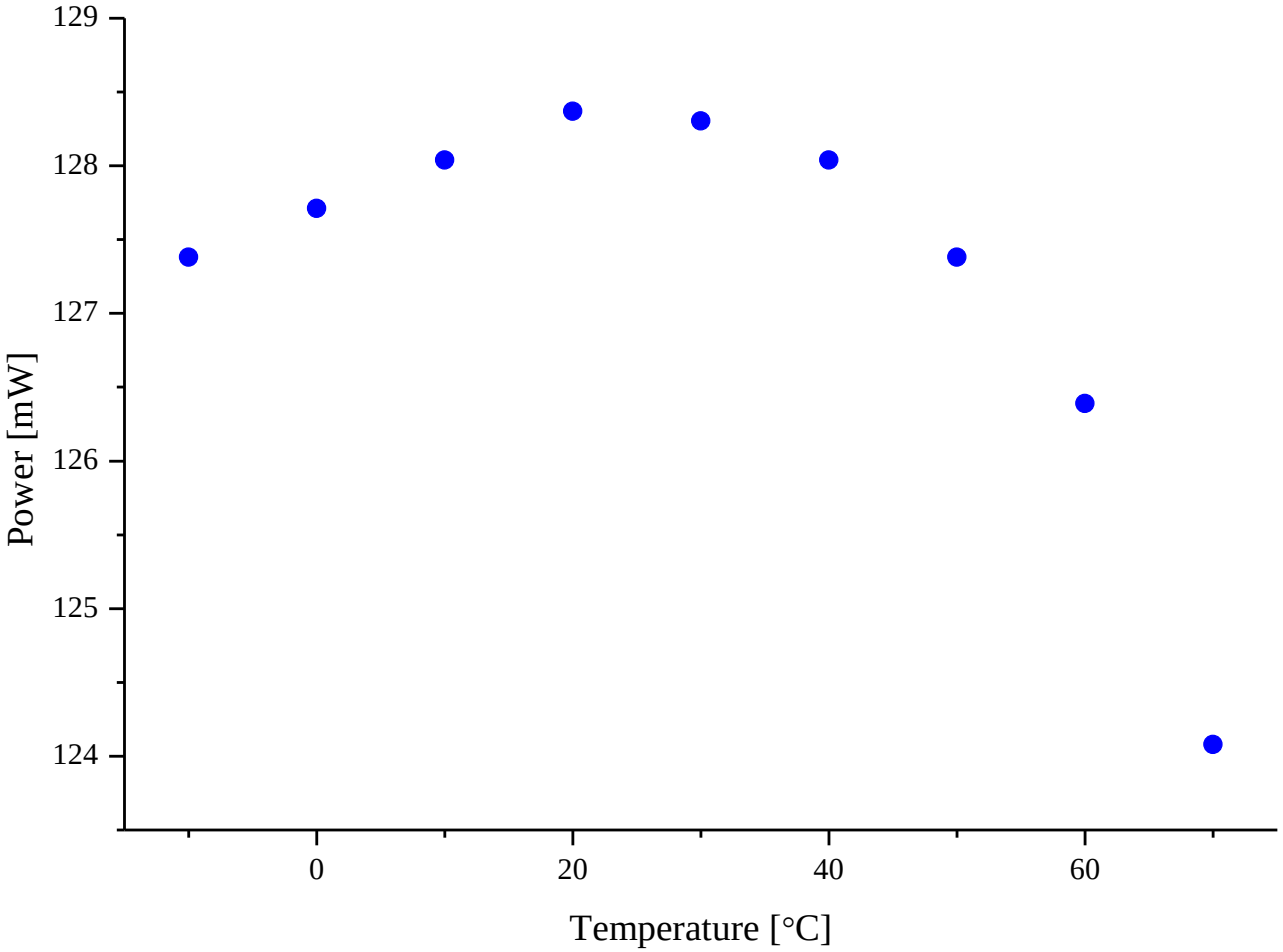
Long-term Stability



Retrace


Frequency, pp10^10
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
Time, Days
Retraces
25
20
15
10
5
0
-6
-4
-2
0
2
4
6
Offset [x10^-11]
RMS = 2.3x10^-11

Power Consumption



The "CSACXO"

- Only operate physics periodically to recalibrate TCXO
- TCXO short-term stability ↔ CSAC long-term drift
- Average power consumption < 30 mW
  - < 20 mW in TCXO-only mode
  - < 150 mW during physics warmup (≈ 2 minutes)
  - < 125 mW during full operation interval

Example:

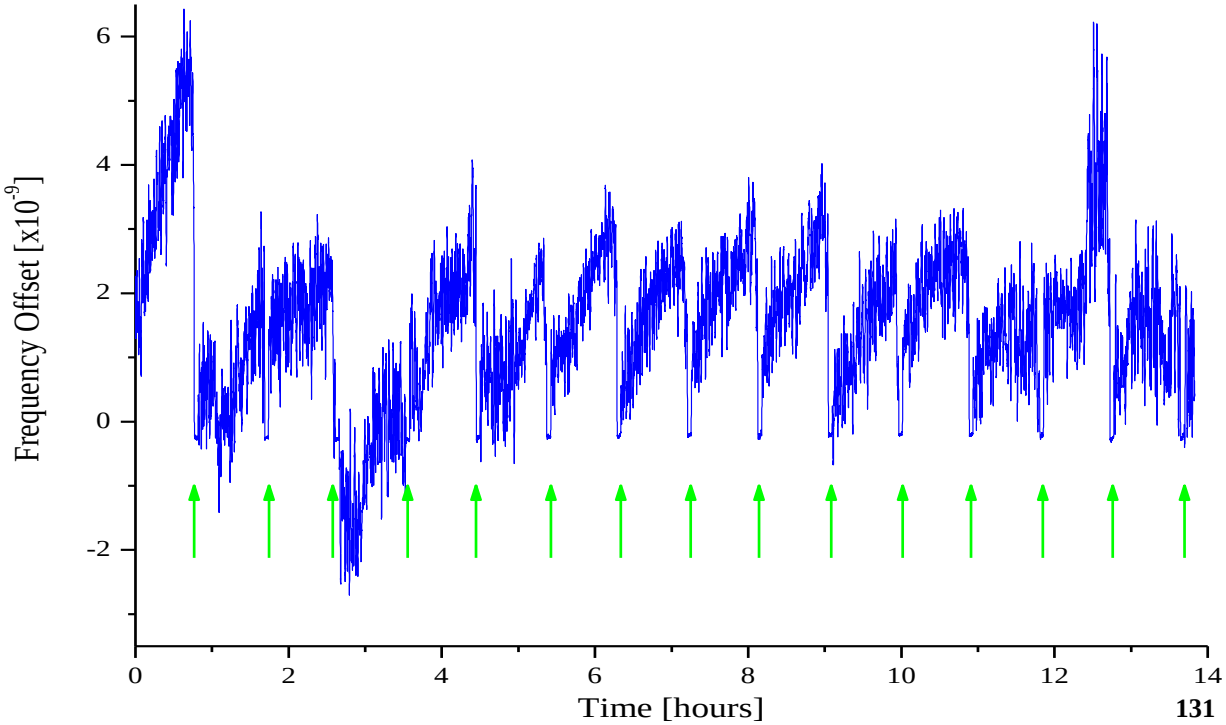
1-hour period

55 minutes TCXO-only

2-minute warm-up

3-minute calibration

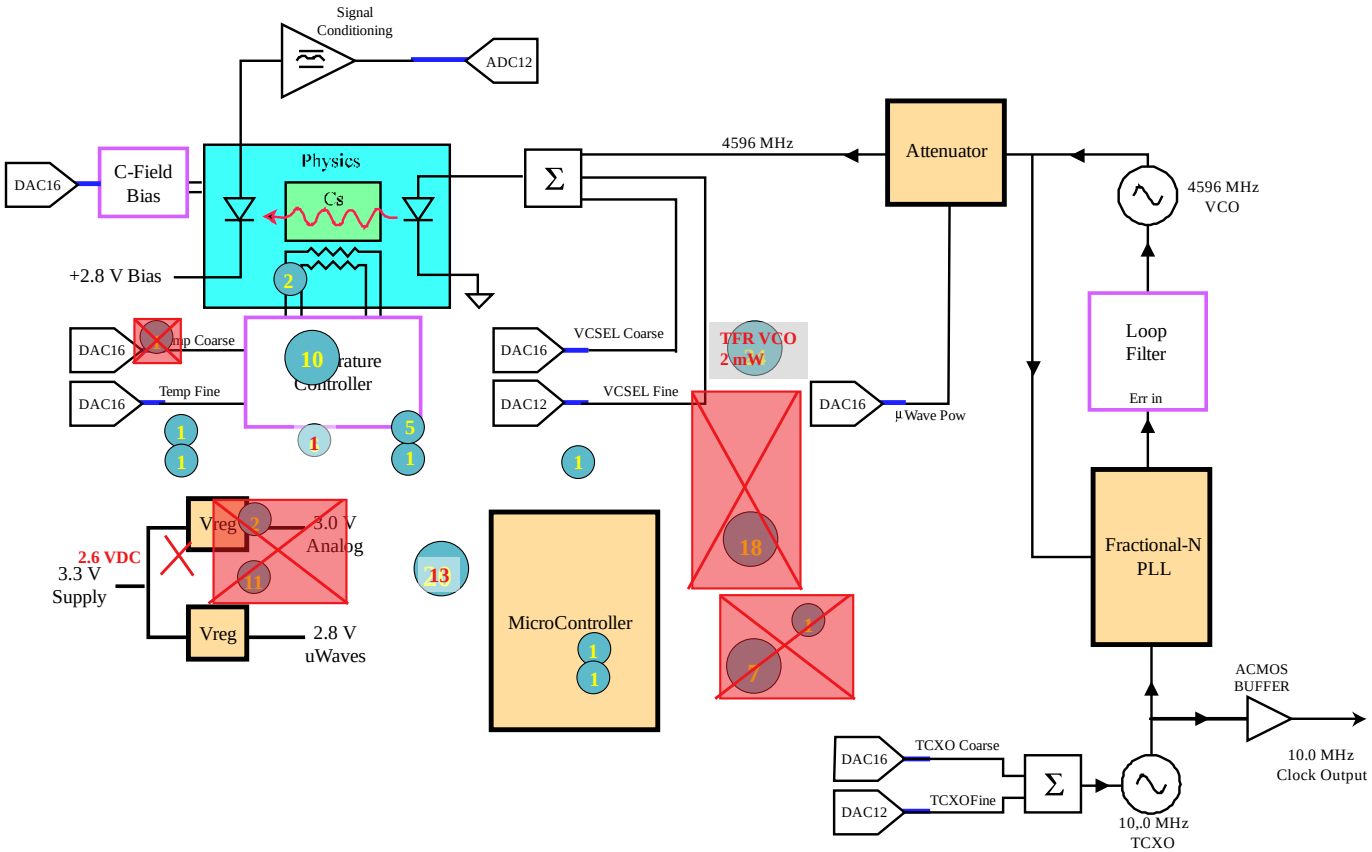
Average power < 30 mW



The 1 cm^3, 30 mW CSAC

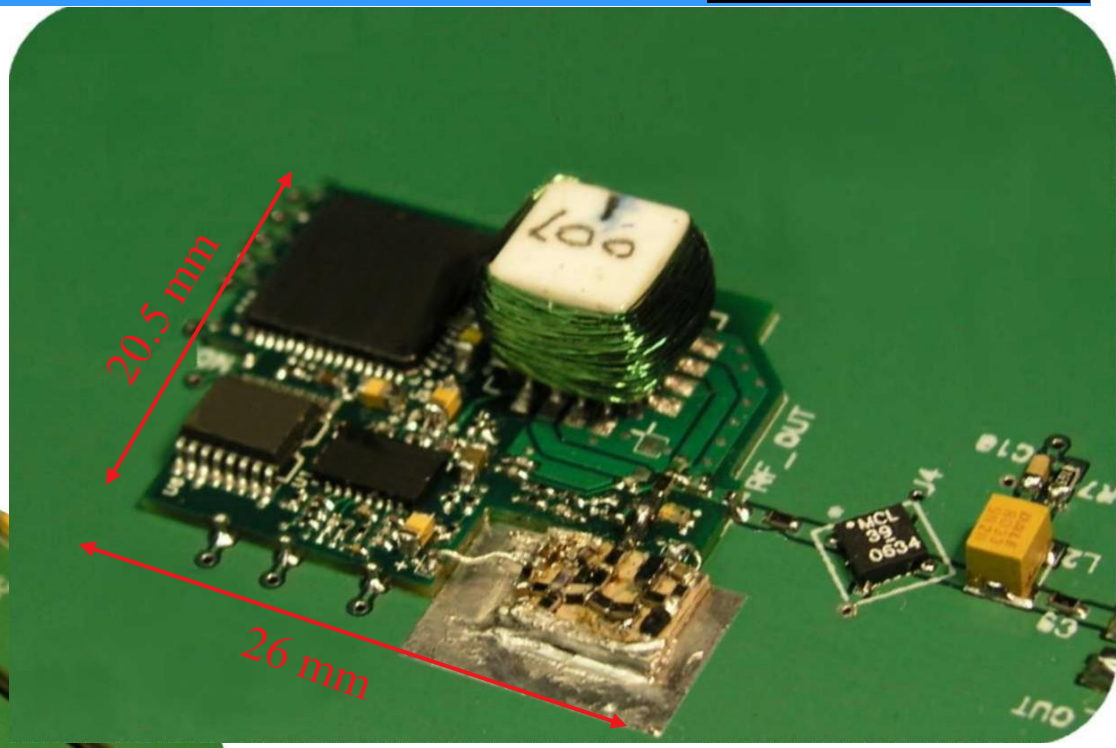
Block Diagram (30 mW?)

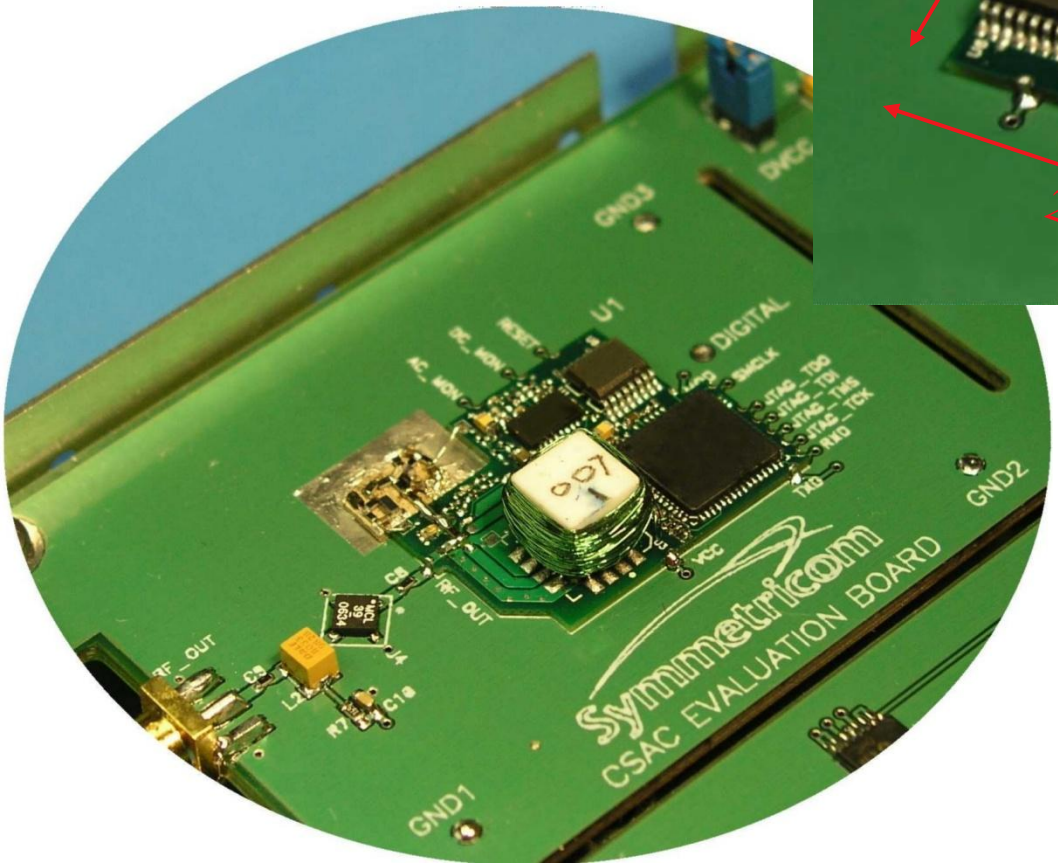
Symmetricom



Microwave System: ~~50 mW~~	→ 28	→ 10	→ 2					
Control System: ~~40 mW~~				→ 35	→ 33	→ 26		
Physics: 10 mW							→ 1	
Regulators & Passives: ~~15 mW~~								
Total: ~~115 mW~~	→	→ 81	→ 73	→ 68	→ 66	→ 59	→ 45	→ 30
	TFR VCO	PLL	TCXO/buffers	Heater	C-Field	Firmware	Vreg	Vcc

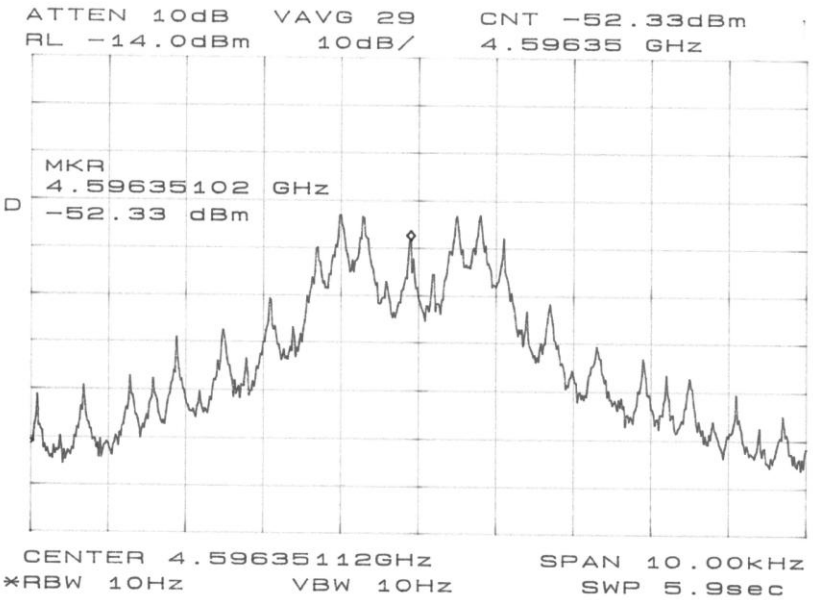
Photos of 1 cm^3 30 mW CSAC



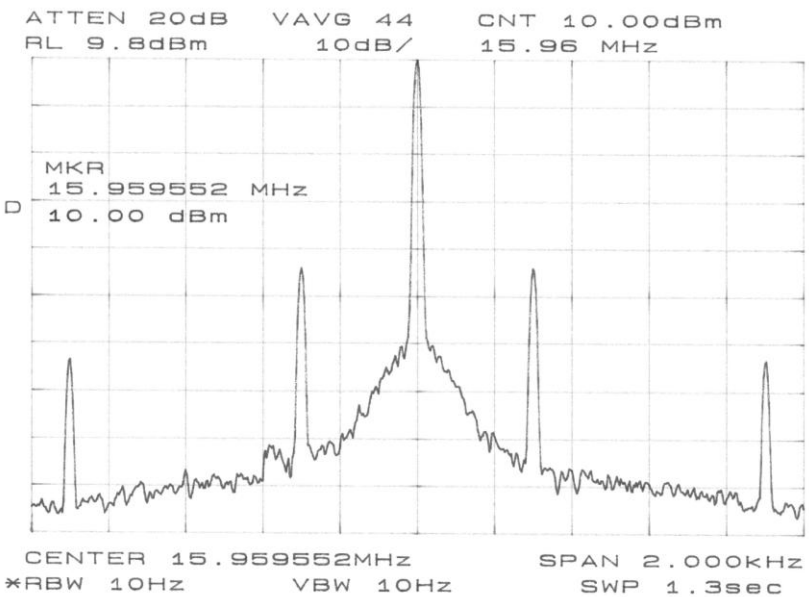


Volume ≈ 1.0 cm^3 *Including bias coil*

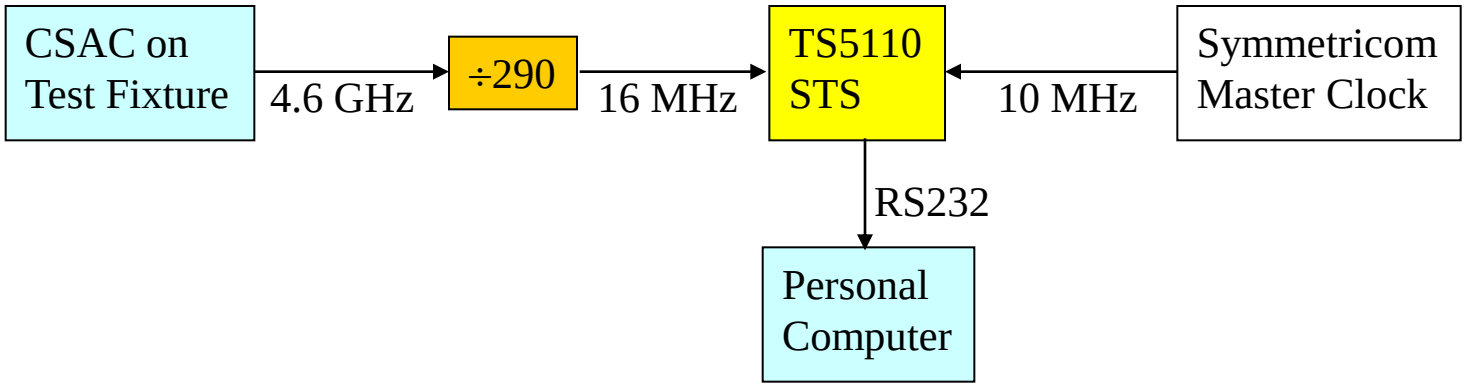
1 cm^3 CSAC Output Spectrum



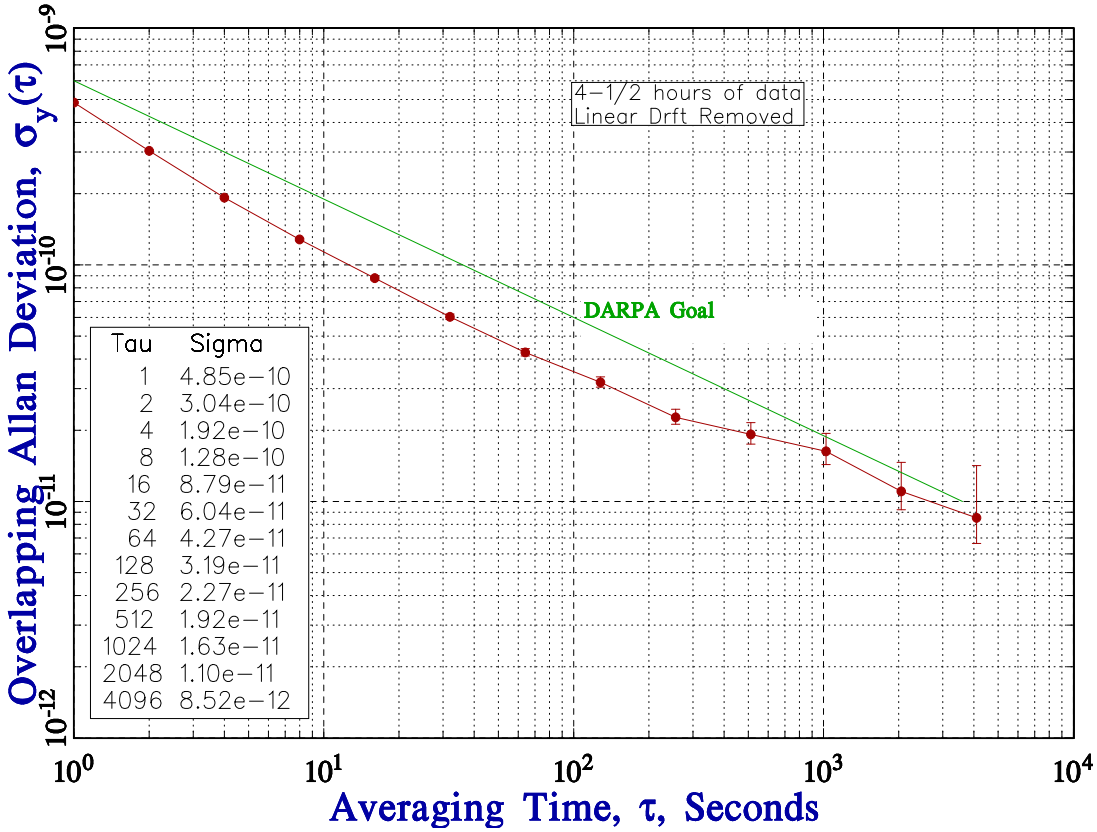
CSAC Output @ 4.6 GHz



Divided down to 16 MHz



1 cm³ CSAC Stability



- Measured in laboratory ambient temperature ≈22ºC
- Input power 10.5 mA @ 2.8 VDC (29.5 mW)
- Clock output @ 4.635 GHz divided by 290X to 16 MHz

At what cost 1 cm^3 CSAC ?

- No microwave synthesizer
  - Output is ≈4.635 GHz *(depending on buffer gas pressure, tempCo, etc.)*
  - No calibration/steering via RS232
  - Output phase noise of VCO contaminated by modulation sidebands
- No voltage regulators
  - Host must provide clean, regulated 2.6 VDC
- No magnetic shielding
  - Host must provide local and system shielding

Summary

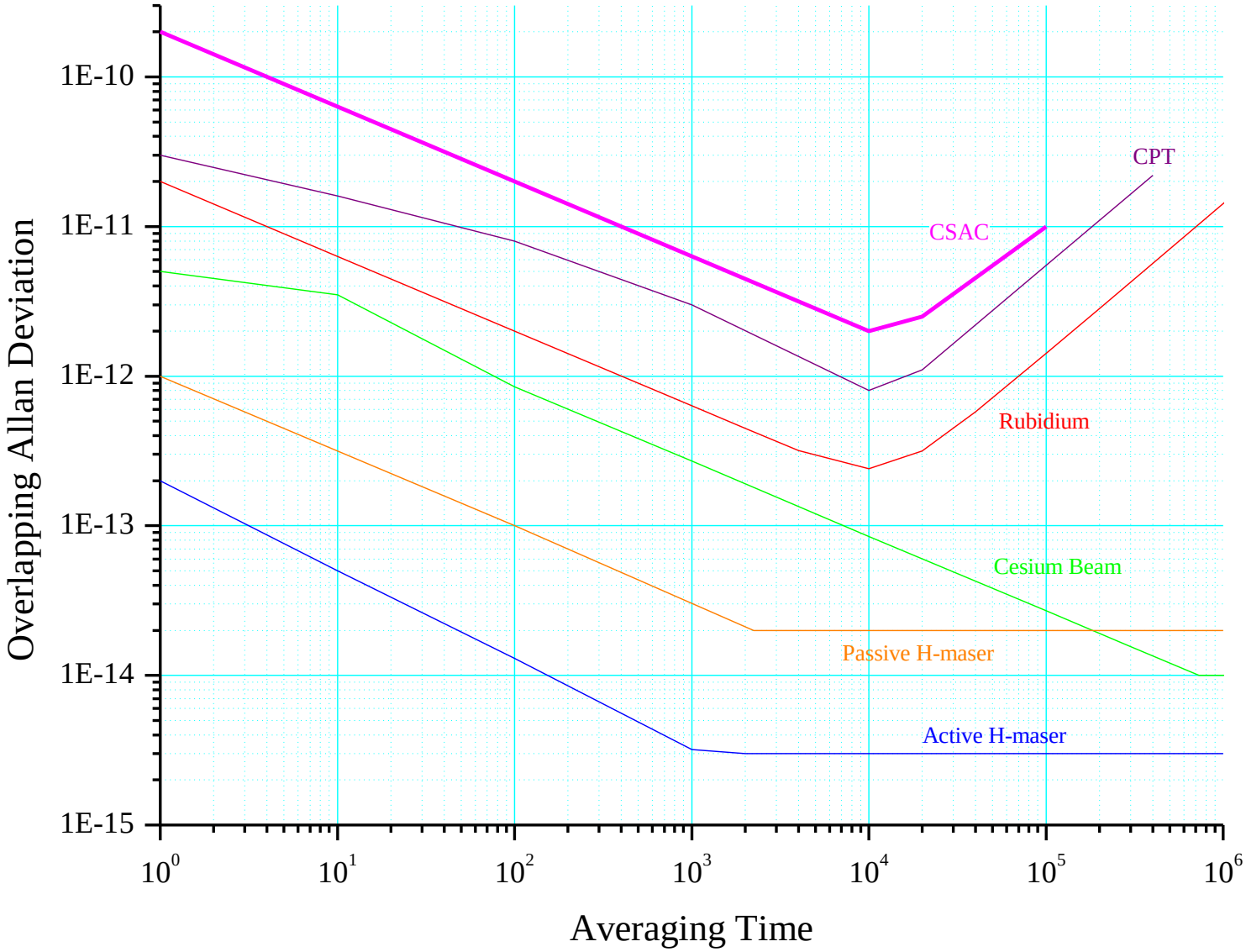
Key concepts

$$\sigma(\tau = 1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$

$$Q = \nu_o / \gamma$$

- Short-term instability is determined by Equation 1:
  - ν_0 is resonance frequency of atom
    - Cesium = 9.2 GHz, Rubidium = 6.8 GHz, Hydrogen = 1.4 GHz
  - γ is linewidth, limited by interrogation technique
    - Fourier transform limit due to Time-of-flight (CFS)
    - Decoherence due to collisions with buffer gas and other atoms (RbO, CPT)
    - Decoherence due to collisions with walls (H maser)
  - $(S/N)_{1\ \text{Hz}}$ is Signal/Noise measured in a 1 Hz bandwidth
    - Limited by statistical shot-noise of atoms (CFS)
    - Limited by electronic noise (H maser)
    - Limited by shot noise of background light (RbO)
    - Limited by laser frequency noise (CPT, CSAC)
- Medium-term instability is dominated by environmental perturbations
  - Mostly temperature, but also pressure, humidity, magnetic fields, etc.
- Long-term instability is limited by aging of physics package properties
  - Changing buffer gas pressure/composition (RbO, CPT, CSAC)
  - Changing wall properties (H maser)
  - Changing laser properties (CPT, CSAC)

Industrial Atomic Clocks Summary



Acknowledgements

I am grateful to several of the CSAC competitors who generously provided material for this tutorial, particularly:

- NIST – John Kitching and Svenja Knappe
- Sarnoff Corporation – Alan Braun
- Honeywell Corporation – Dan Youngner
- Teledyne Scientific – Jeff DeNatale

Always the Symmetricom CSAC team:

- Symmetricom Beverly
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