IMPACT

Integrated
Micro
Primary
Atomic
Clock
Technology

Industry Day

May 15, 2008

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HERMIT, CSAC, MX, NGIMG, HI-MEMS, NEMS, MINT, IMPACT
Microsystems Technology Office (MTO)
Defense Advanced Research Projects Agency

IMPACT Industry Day Objectives

- Share expertise pertaining to atomic clock miniaturization
- Form working collaborations – also facilitated by web-page
- Q&A with DARPA PM

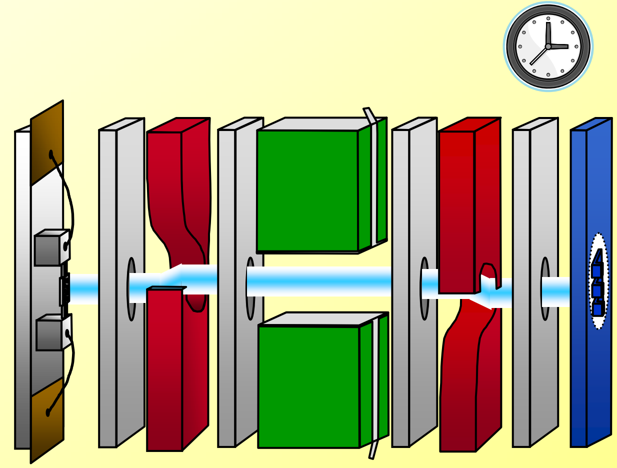
IMPACT Industry Day Schedule

9:00 AM IMPACT Introduction
Amit Lal, DARPA
9:30 AM ColdQuanta – Developer and Supplier of Ultracold Devices
Rainer Kunz, ColdQuanta, Inc.
9:50 AM Narrow Linewidth VCSELs for IMPACT Program
Chuni Ghosh, Princeton Optronics, Inc.
10:10 AM High Efficiency, Large Signal-to-Noise Ratio, and Low Power Atomic Clock Based on Polarization Self-Switching VCSEL and Tunable MEMS
Stephen Chou, Princeton University
10:30 AM Break
10:50 AM Ultra-compact, Monolithically Integrated, Precision Photonic Platform for IMPACT Applications
S.J. Ben Yoo, University of California, Davis
11:10 AM In situ Gas Purification and Vacuum Control in Sealed Cavities
Scott Wright, University of Michigan
11:30 AM Symmetricom Capabilities for IMPACT Collaboration
Mike Garvey, Symmetricom
11:50 AM Lunch
12:35 PM TBD
Bob Newgard, Rockwell Collins
12:55 PM Local Oscillators and Mass Sensors for IMPACT
Eun Sok Kim, University of Southern California
1:15 PM Capabilities of the KCI Team
Martin Levine, Kernco, Inc.
1:35 PM – 3:30 PM Discussion/Q&A

Integrated Micro Primary Atomic Clock Technology

VISION

Develop miniature absolute frequency and time standards (i.e. no calibration necessary) that achieve fundamental stability limits (1-5 ns/day time loss)

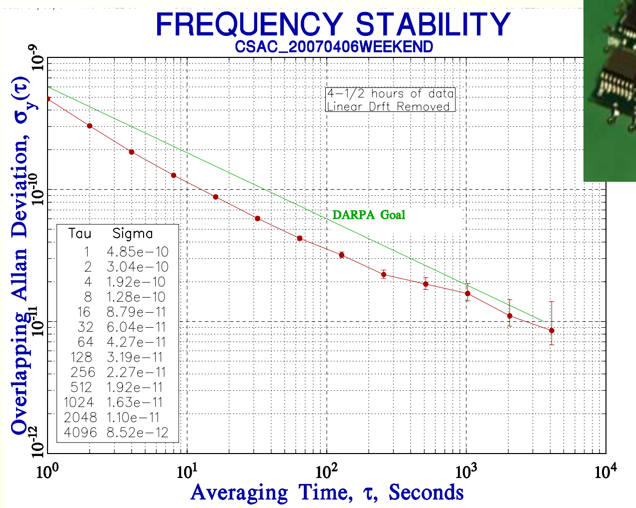


OBJECTIVES

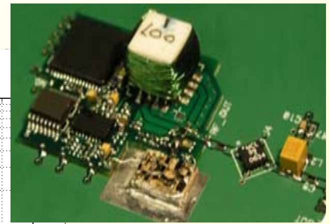
- Leverage CSAC and NGIMG technology, to develop MEMS/NEMS atom manipulation : sample atomic transition frequencies in atom beams, traps, and masers - to generate primary time and frequency
- Keep power and volume tiny for nano-pico satellites, underwater vehicles, UAVs, sensors, portable MBE like fabrication tools, etc.

CSACs at End of Phase III

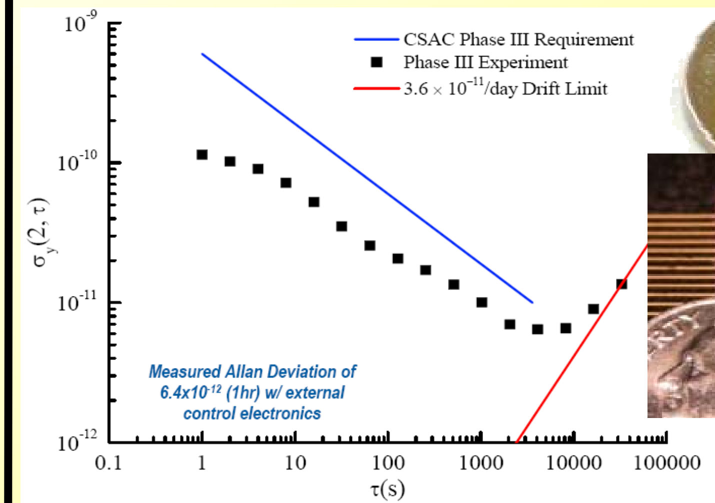
Symmetricom

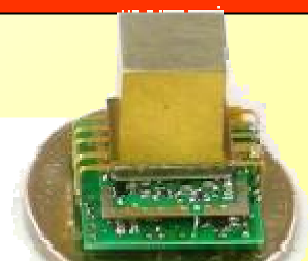


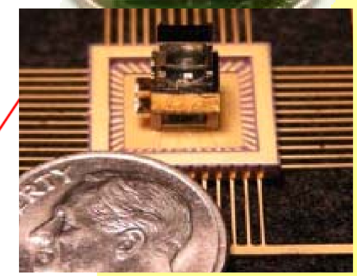
Tau	Sigma
1	4.85e−10
2	3.04e−10
4	1.92e−10
8	1.28e−10
16	8.79e−11
32	6.04e−11
64	4.27e−11
128	3.19e−11
256	2.27e−11
512	1.92e−11
1024	1.63e−11
2048	1.10e−11
4096	8.52e−12



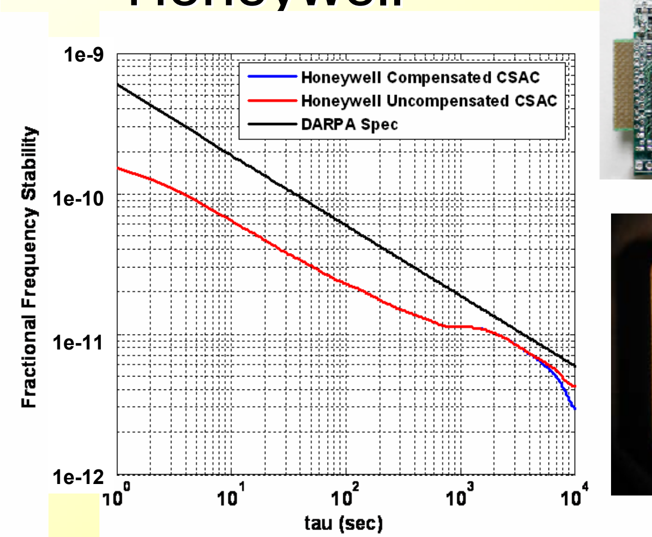
Teledyne

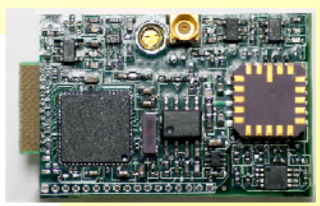


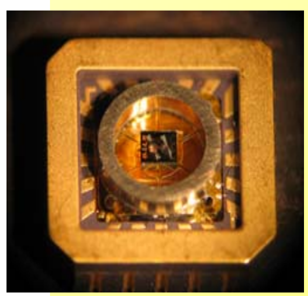




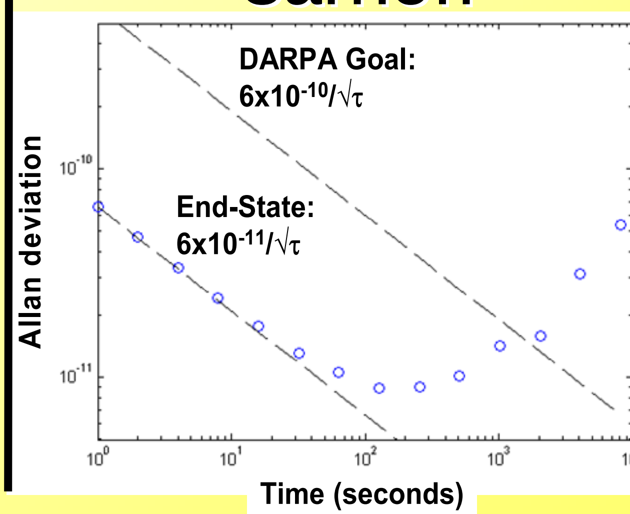
Honeywell

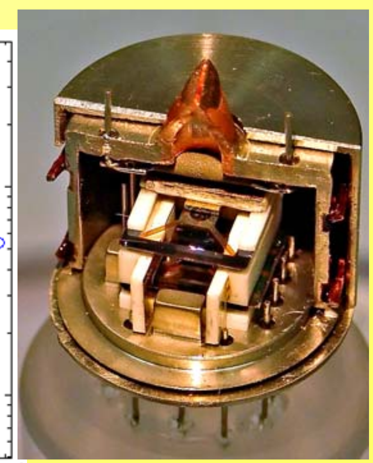






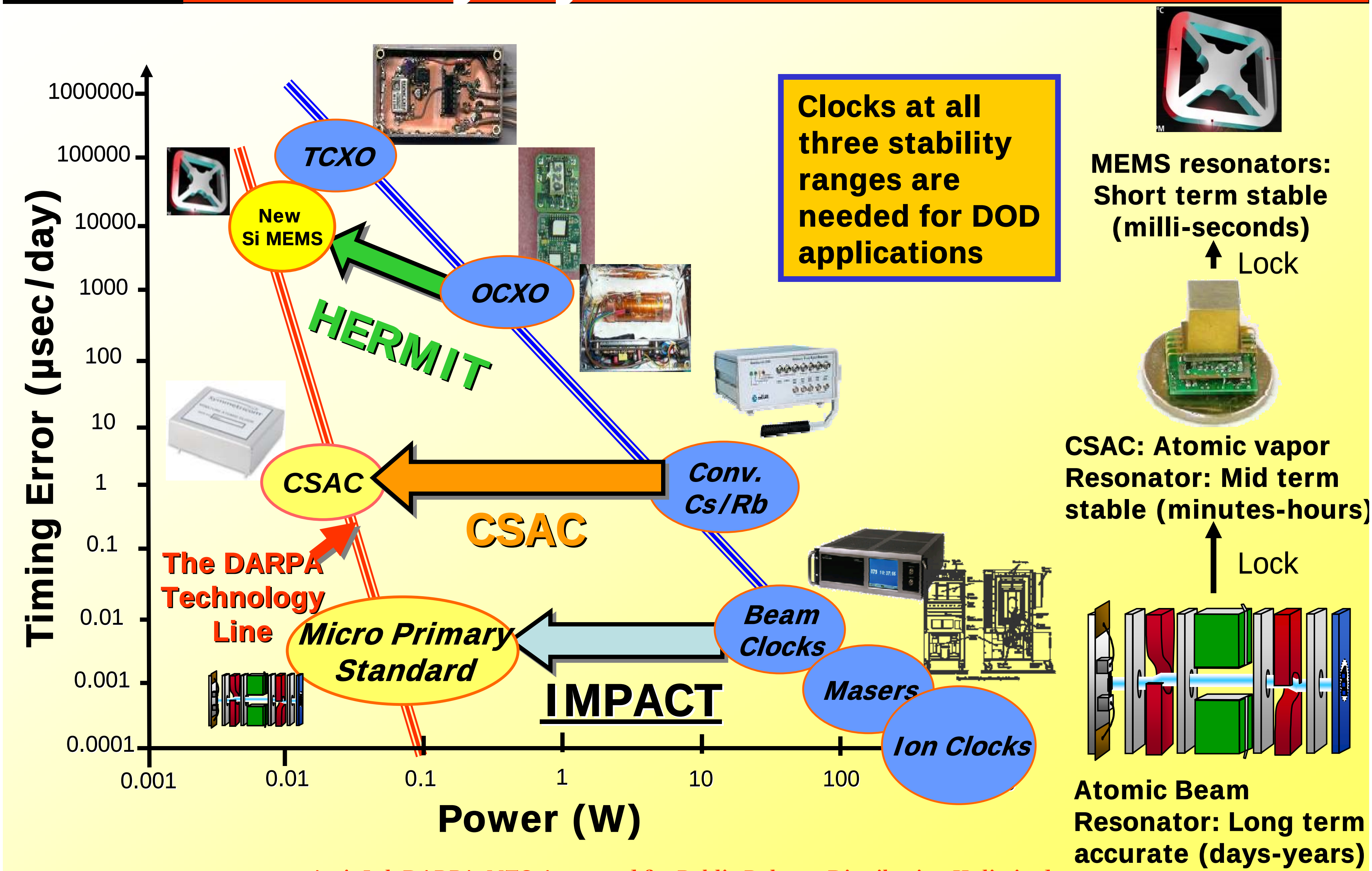
Sarnoff



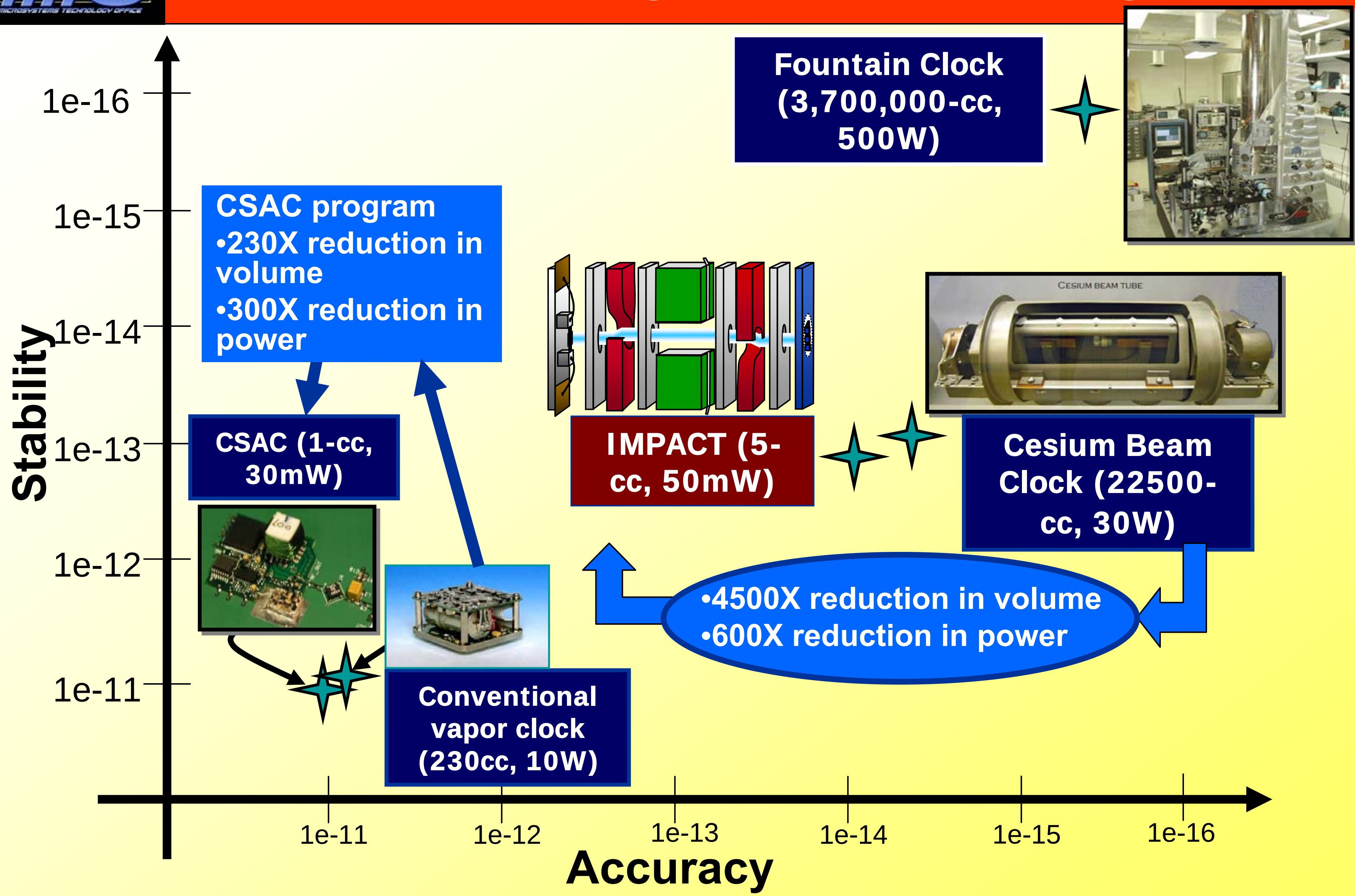


8 mm scale, 4 cm^3 CSAC

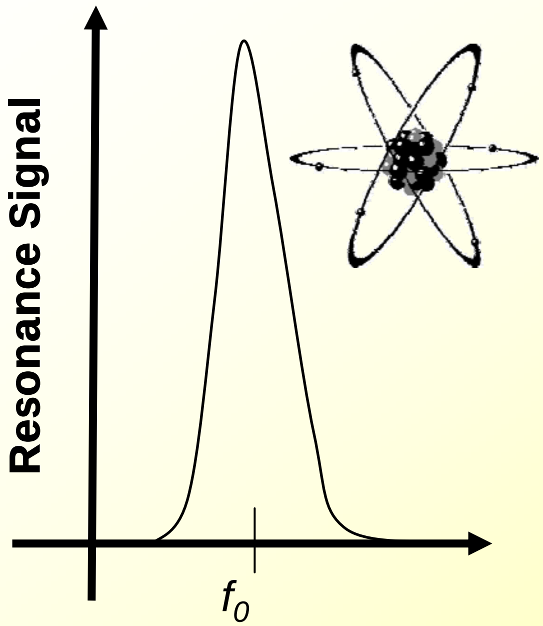
IMPACT: Improves Stability and Accuracy by 100-1000X over CSAC



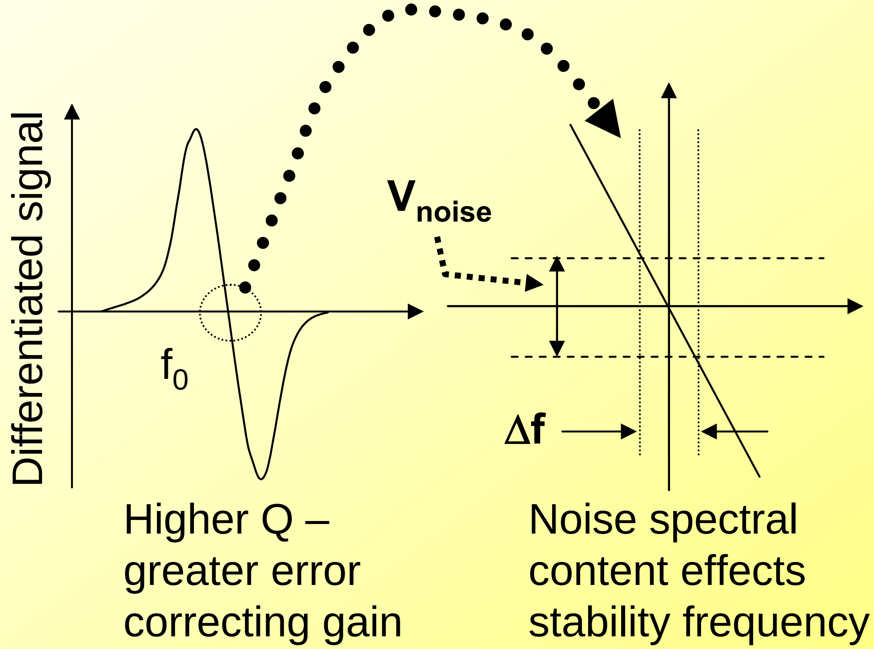
Accuracy vs. Stability



Precision and Accuracy of Atomic Resonators



$$f_0 = f(t, T, B, E, p, n_i)$$



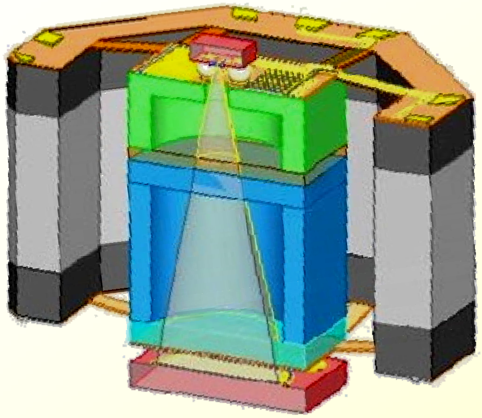
$$\sigma \approx \frac{1}{Q * SNR}\Big|_{1-Hz}$$

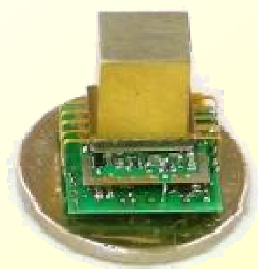
- **Accuracy: stay at a constant frequency over time**
- **f_0 drifts over time resulting in clock error**

- **Precision (stability) – stay at same frequency over time**
- **Statistical noise results in clock error**

IMPACT compared to CSAC

Atom Vapor Clocks (CSAC)



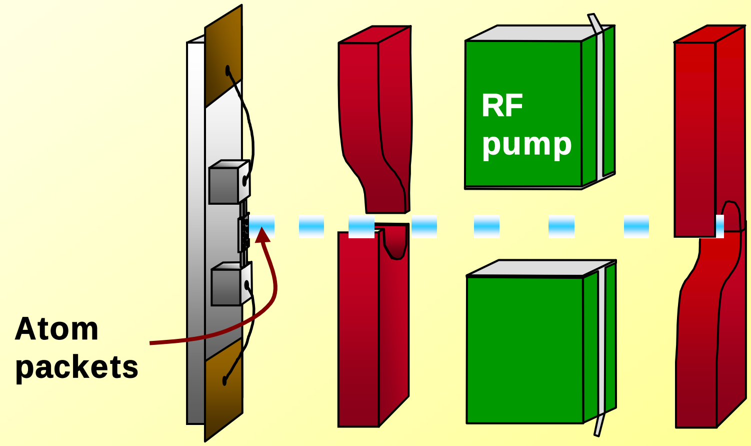


Vol: 1cm^3 Power: 30mW
Stability: 1x10^{-11}
10 μs/week time loss

Subtle changes effect atom transition frequency:

- **Buffer gas pressure: Cs/Rb atoms are in a sea of buffer gas (N_2, Ar). Buffer gas atom interacts with alkali atom to shift resonance frequency: 50Hz/Torr → 10^{-2} torr shift leads to 10^{-11} frequency shifts**
- **Wall opacity aging causes increased light → Increase light shift frequency aging**

Primary Clocks (IMPACT)

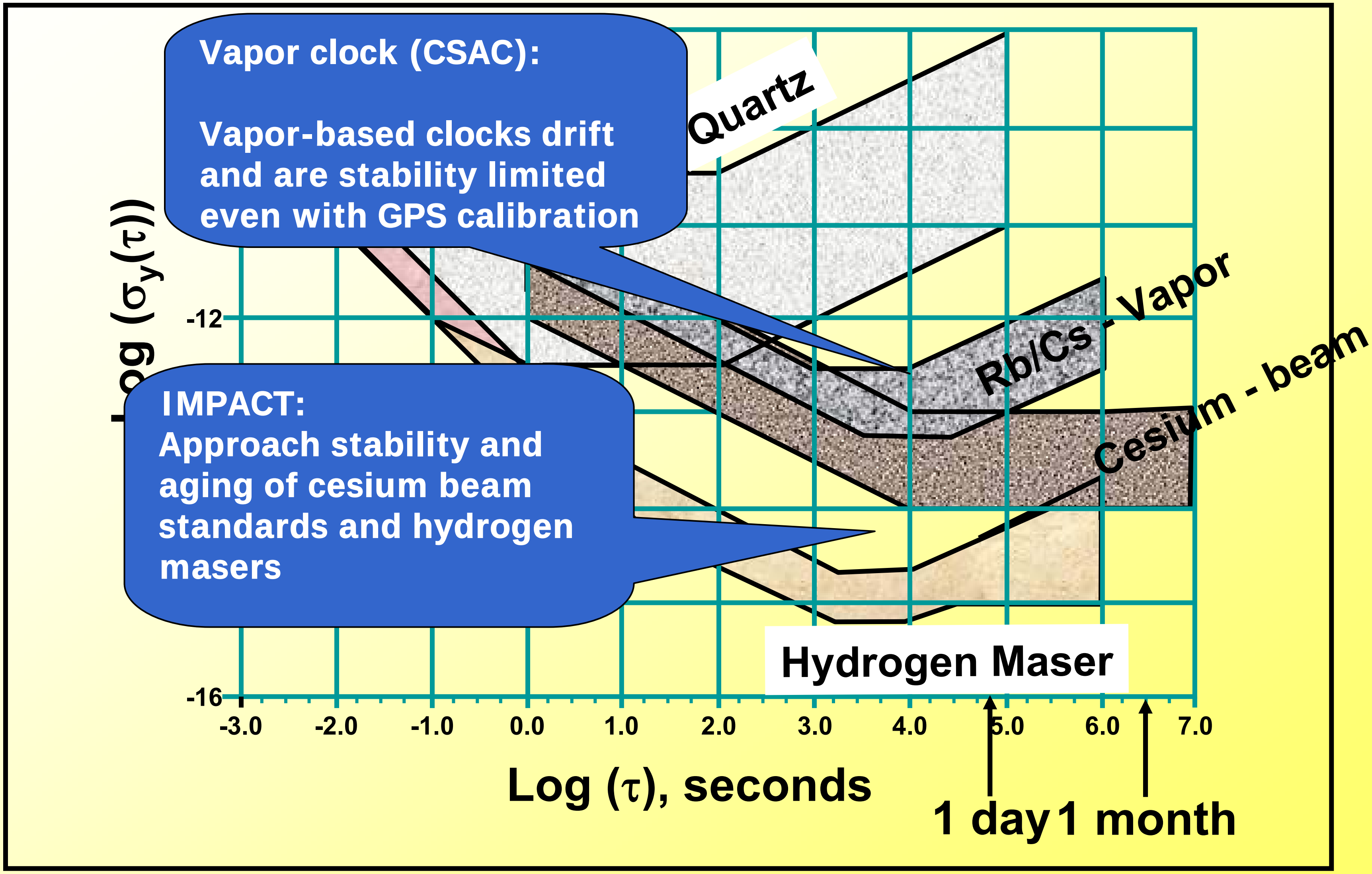


Vol: 5 cm^3, Power: 50 mW
Stability: 1x10^{-13}, Acc: 1x10^{-14}
(1 μs time loss over one year)

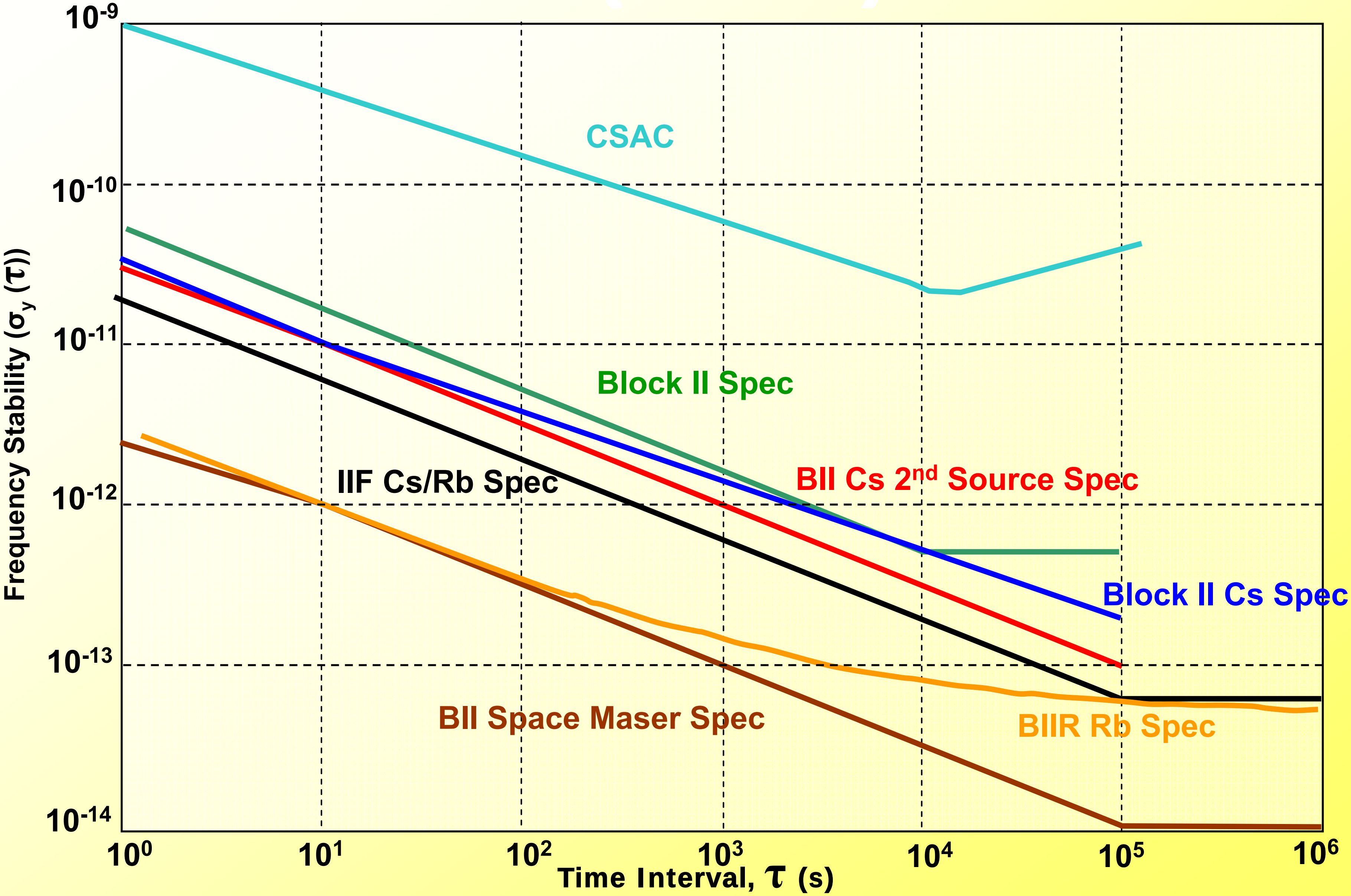
Atoms transitions are sampled in vacuum:

- **Atom Beam: Atoms are shot out in a beam in which they do not collide with themselves or with background atoms**
- **Atom Traps: Atoms are trapped and sampled in absence of other atoms**
- **Masers: RF directly output from low-density atom stimulated emission**

Stability Ranges of Clocks



SPACE Clock Specifications (USNO)



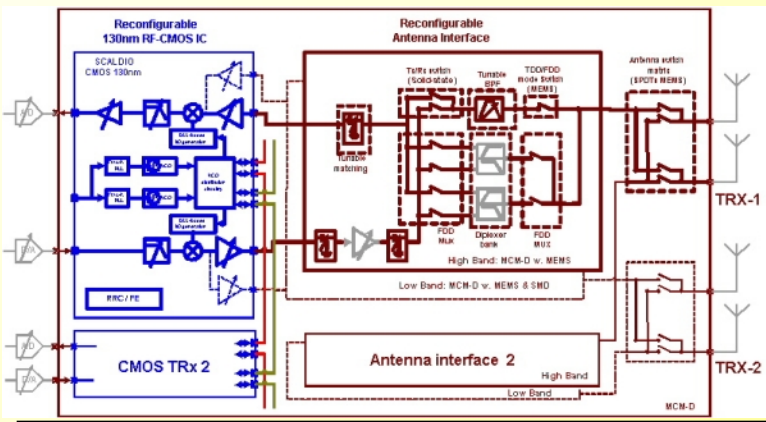
IMPACT Applications

Satellite Constellations

Space grade Beam Clock: 3000cc, 30Watts → IMPACT <10cc, <75mW

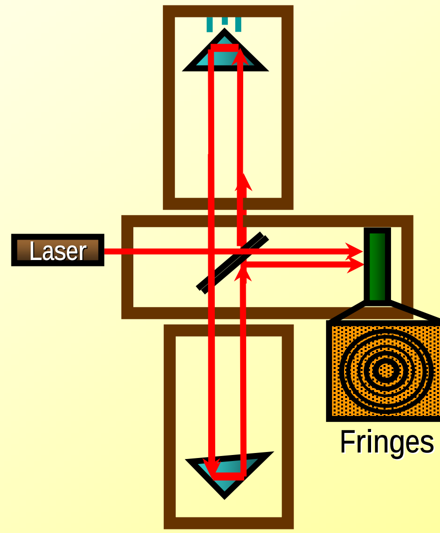
Independent drift-free clock for GPS satellites. e.g. 10,000 GPS satellites, satellite constellations, accurate time stamping

Pulse radios



Reduce requirements for PLL, fixed frequency will enable dispersion measurement. Reduced guard band in fast comms, accurate RADAR

µ-Absolute Gravimeter



Need µ frequency and optical wavelength standard for a 5-cc gravimeter

UAV, sensor node compatible gravimeter

Underwater Unmanned Vehicles

No resurfacing necessary, and absolute timing can be sustained for 4-5 years

Technology "Toolbox"

CSAC Derived Technology

Physics package

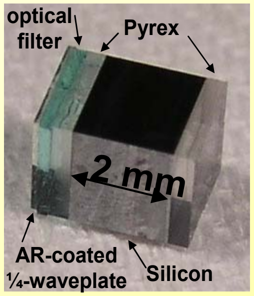
- *Cs and Rb storage and fill technology*
- *4000 ºC/W polyimide supports, 10 μm design-rule Pt heater/temp sensors*

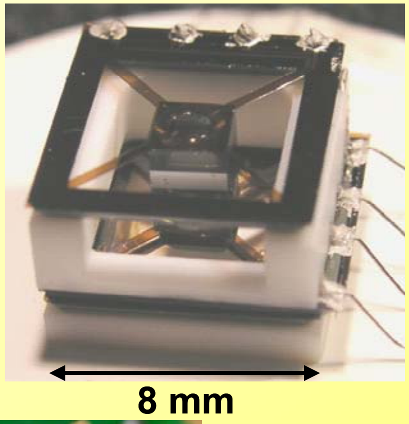
RF interrogation:

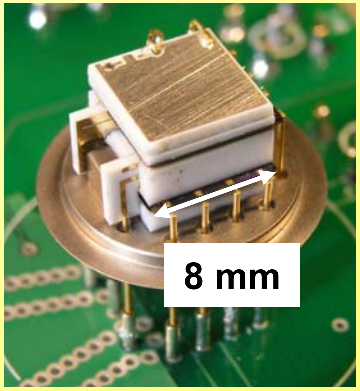
- *Millimeter-sized near-field 9.2 GHz structures, 0 dBm drive*

VCSEL lasers:

- CW and high speed (10 GHz), low power consumption (300 μA thresholds), low noise



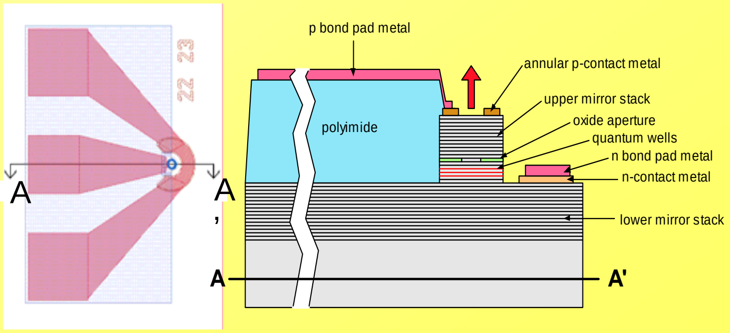




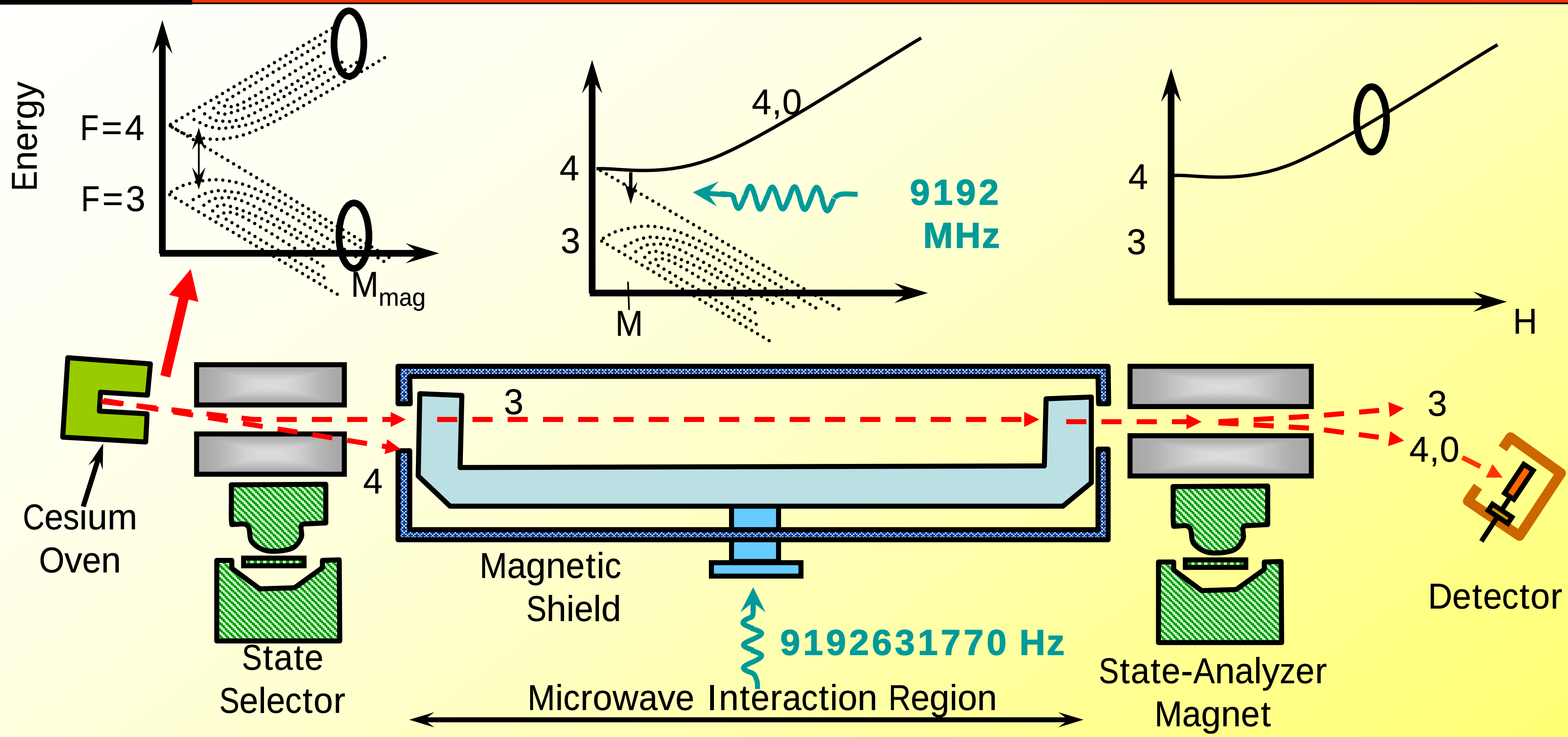
NGIMG Derived Technology

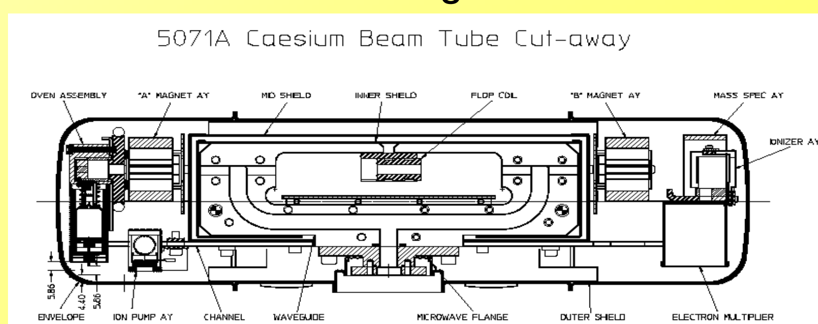
Uniform magnetic field region/shielding:

- 0.5% uniformity from Helmholtz coils (measured from atomic linewidth)



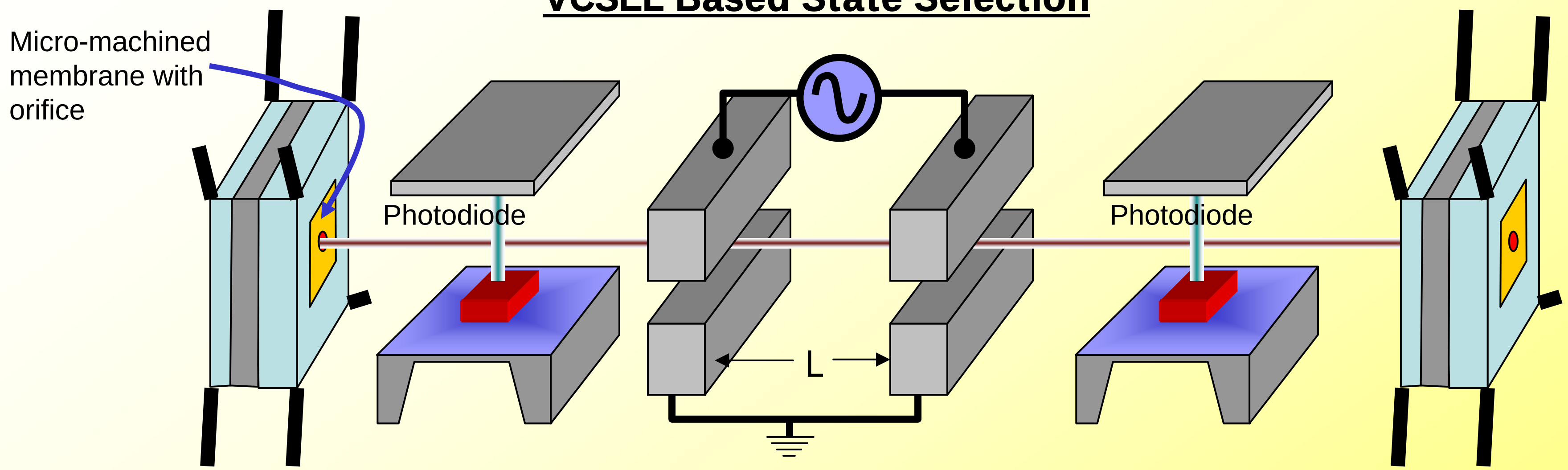
Cesium Atomic Beam Clock



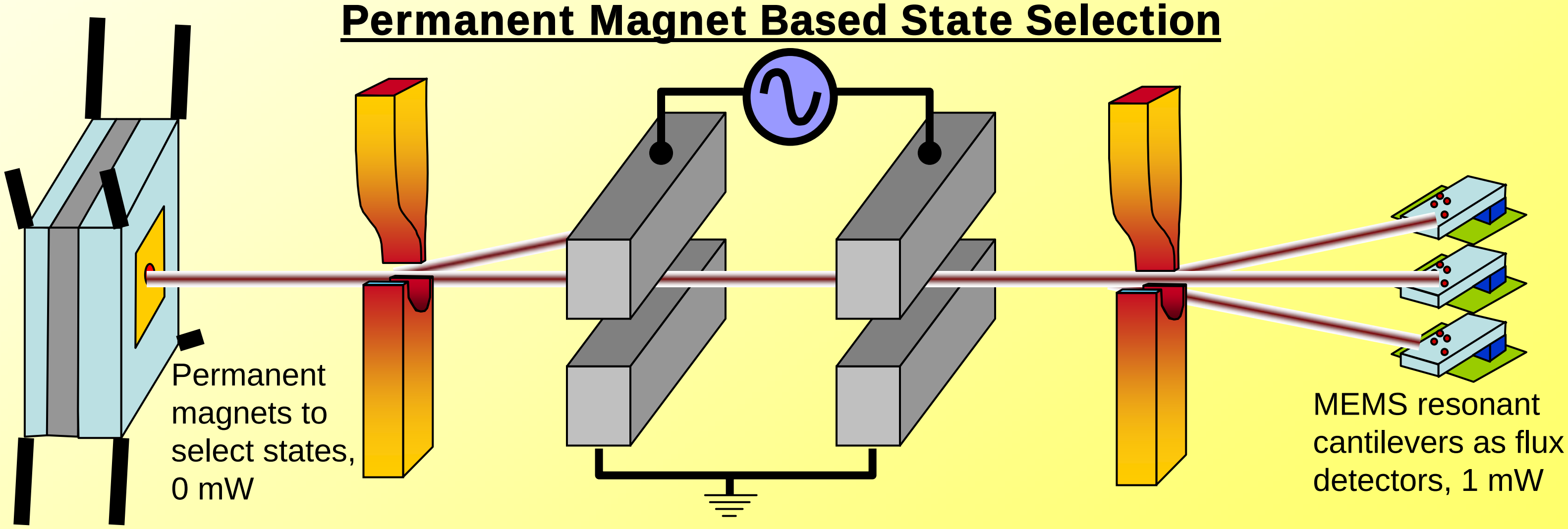


Micro Beam Clock Architectures

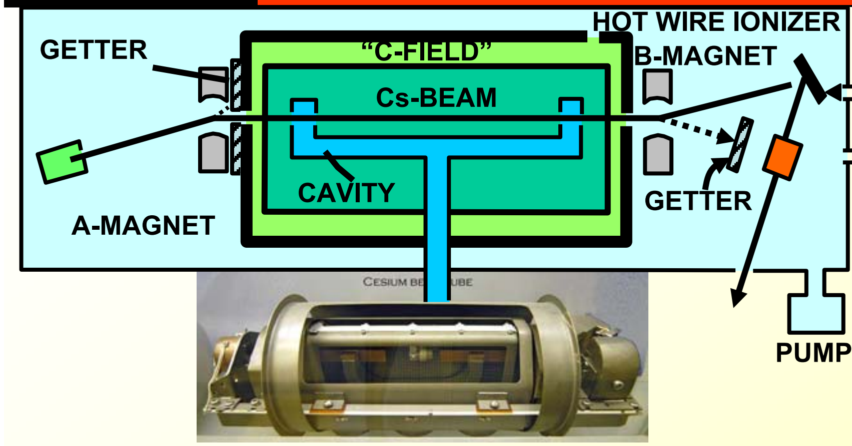
VCSEL Based State Selection



Permanent Magnet Based State Selection

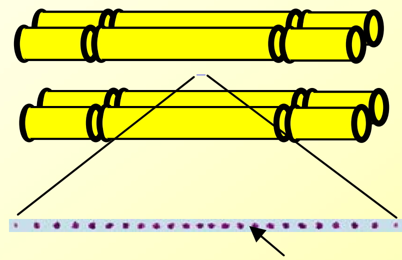


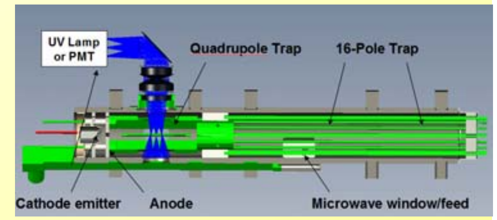
IMPACT Approaches



Macro Beam Clock: Q ~ 3-4*10^7, SNR~10^3

Beam intensity, High S/N atom flux detector

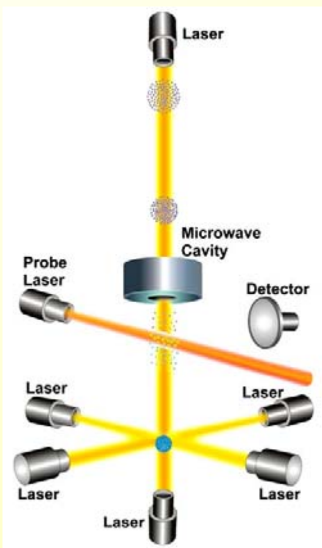


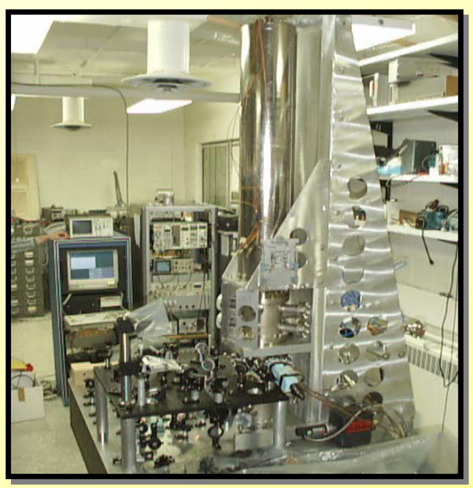


Ions are trapped and interrogated optically in quadrapole fields

Ion Array Clock: Q ~ 3-4*10^{11}, SNR~10^2

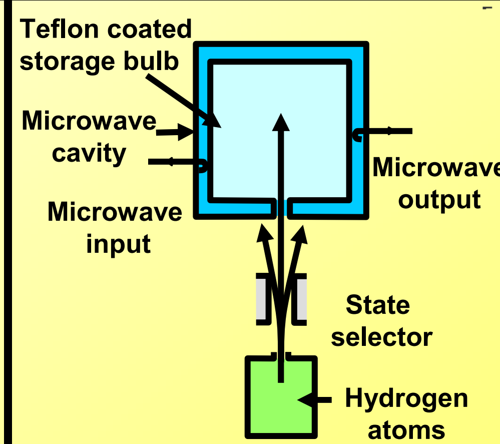
Low-power discharge lamp

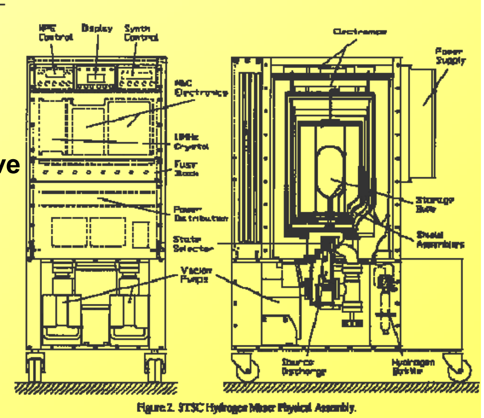




Magneto Optical Trap: Q ~ 3-4*10^{10}, SNR~10^3

Laser power for trap, parasitic laser signal in detector





Hydrogen Maser: Q ~ 3-4*10^7, SNR~10^5

High vacuum, low-power hydrogen source, dielectric loaded cavity

Revised IMPACT GNG Milestones

Milestone	SOA	Phase I	Phase II	Phase III
Power (mW) @ RT	30000	160 (physics package)	250 (total clock)	<50 (total clock)
Size (cc)	22500	30 (physics package) - maximum dimension in any direction <10cm	20 (total clock)	5 (total clock)
Atom detector Q*S/N	1.00E+10	1.00E+10	2.00E+10	5.00E+10
Time Loss (ns) @ 1 ms	3.2E-03	3.2E-03	1.6E-03	6.3E-04
Time Loss (ns) @ 1 second	1.0E-01	1.0E-01	5.0E-02	2.0E-02
Time Loss (ns) @ 1 hour	6.0E+00	<60	6.0E+00	1.2E+00
Time Loss (ns) @ 1 day	2.9E+01	<300	2.9E+01	5.2E+00
Time Loss (ns) @ 1 month	1.6E+02	<1600	1.6E+02	3.2E+01
Fractional Frequency Retrace (1-hour turn on time every day)	1.00E-13	1.70E-11	1.00E-13	1.00E-13

Phase I: Clock physics package development

Phase II: Miniaturize physics package and electronics, reducing power, improving accuracy and stability

Phase III: Mitigate frequency drift sources with active feedback and/or additional shielding, pursue chip integration for power reduction