Chip-Scale Atomic Clock

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Collaboration

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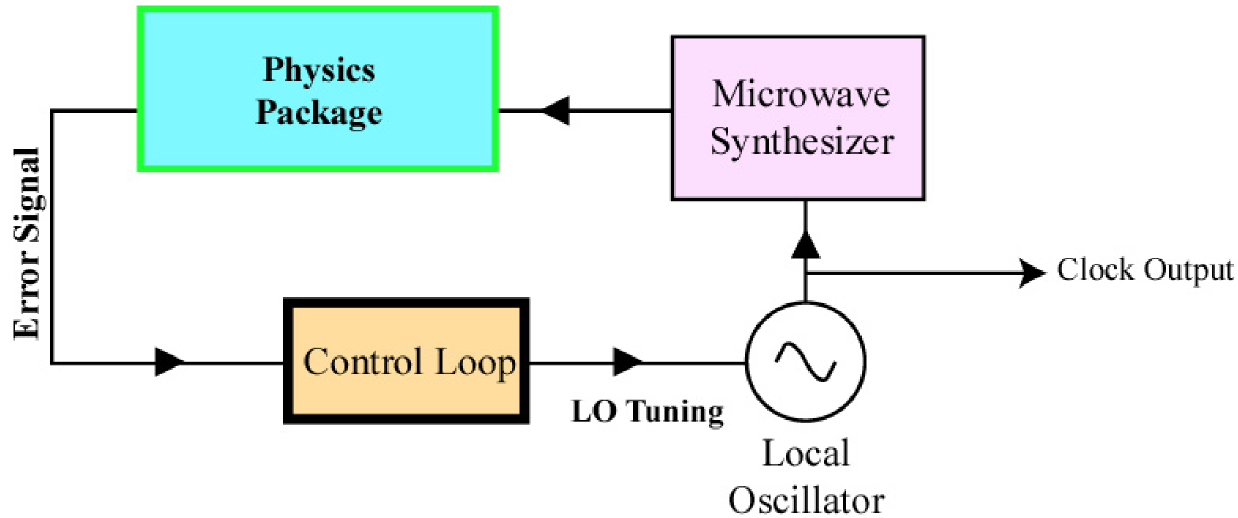
  - *M. Varghese, J. Leblanc, G. Tepolt, and M. Mescher*
- Sandia National Laboratories
  - *D. K. Serkland, K.M. Geib, and G.M. Peake*

- $$$
  - DARPA-MTO Contract No. NBCHC020050

What is an atomic clock?



Atomic resonance is intrinsically more stable than quartz local oscillator

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

Control Loop continuously steers LO frequency to atomic resonance

RF output *(10 MHz)* embodies stability of atomic resonance

Conventional Atomic Clocks

Active Hydrogen Maser
375,000 cm^3
100 Watts
Excellent short-term stability

Cesium Beam Frequency Standard
30,000 cm^3
50 Watts
Excellent long-term stability/accuracy

Rubidium Oscillator
500 cm^3
10 Watts
Compact and cost-effective

The Chip-Scale Atomic Clock

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- DARPA MTO-funded effort to produce accurate timing sources for portable instruments
  - Time-Sequence Code Acquisition for Secure Communications
  - GPS Direct P(y) Code Acquisition
- Key Specifications
  - Device Volume: $< 1\text{cm}^3$
  - Total Power Consumption: < 30 mW
  - Stability: $\sigma_y(\tau = 1\,\text{hr}) < 1 \times 10^{-11}$
- Two orders of magnitude smaller and lower power than current atomic clock technology

CSAC DARPA MTO

DARPA MTO MEMS

The CSAC Challenge

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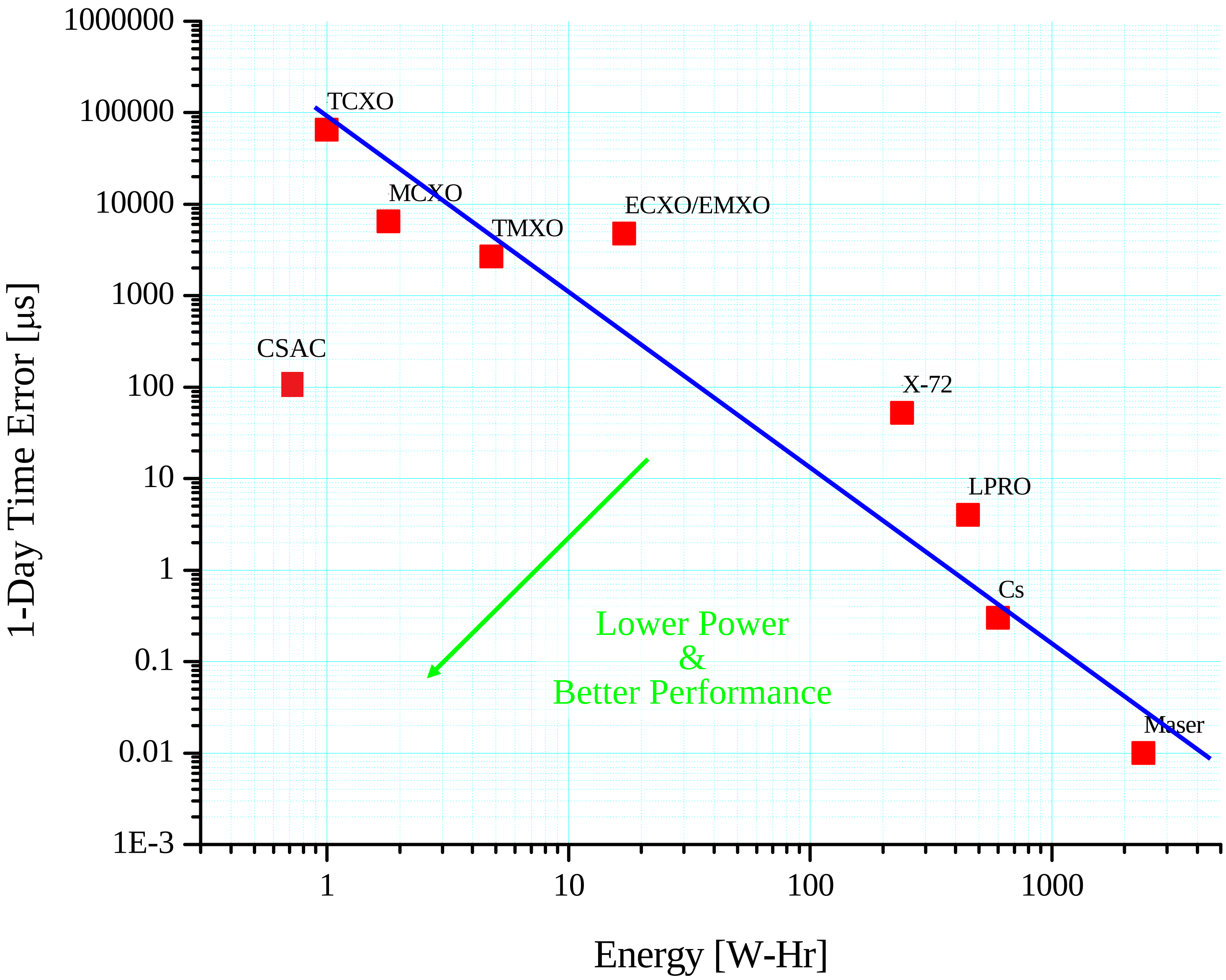

Small low-power atomic clocks

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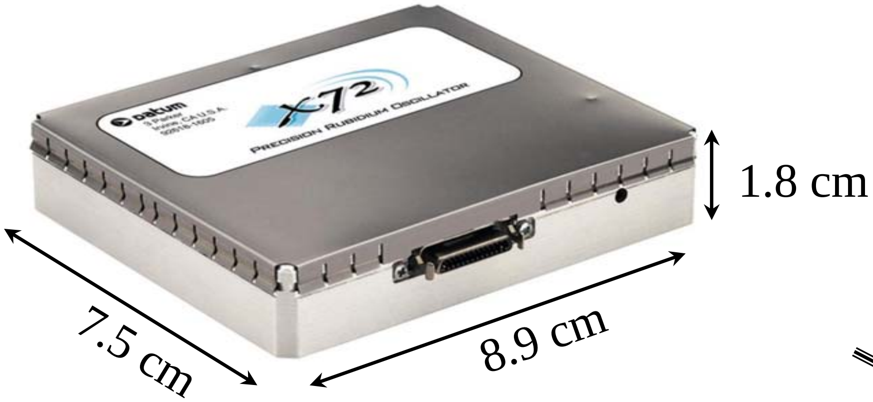
X72



Smallest production atomic clock

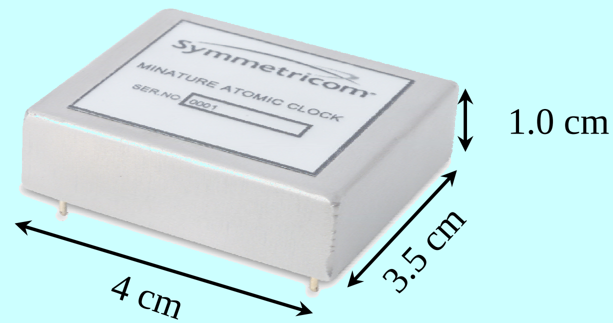
Volume ≈ 125 cm^3

Power ≈ 8 W

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

CSAC Prototype

Miniature Atomic Clock - "MAC"

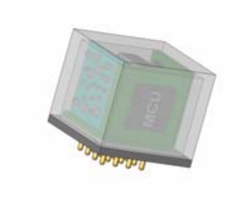


Volume ≈ 16 cm^3

Power ≈ 125 mW

Stability ≈ $3x10^{-10}$ @ 1 second

CSAC Objective



Volume ≈ 1 cm^3

Power ≈ 30 mW

Stability < $6x10^{-10}$ @ 1 second

DARPA MTO CSAC Program

- Multiple Competitive Contracts
  - Symmetricom/Draper/Sandia
  - National Institute of Standards and Technology (NIST)/U. of Colorado
  - Teledyne Scientific/Rockwell Collins/Agilent
  - Honeywell
  - Sarnoff/Princeton/Frequency Electronics

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- Three-Phase Program:
  - Phase-I (2002-2003) – Physics and feasibility
  - Phase-II (2003-2005) – Intermediate size/power prototype
  - Phase-III (2005-2007) – Design Verification and size/power reduction
  - Phase-IV (?) – Environmental Ruggedization, production engineering, and System Integration

Major Challenges

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- Physics Package (10 mW)
  - Must be heated to T>75°C to vaporize (alkali metal) atoms
    - Thermal isolation – *Convection, Conduction, Radiation*
    - Overhead head load – *Low-power-dissipation VCSEL*
  - Mechanical Robustness
    - Shock and vibration resistance for handheld (dropped) applications
- Microwave System (10 mW)
  - Phase noise at microwave frequency (4.6 GHz) must support Signal/Noise
  - Short-term stability at $\tau < \tau_{LOOP}$ must support STS objective
- Control Systems (10 mW)
  - 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…

Low-power Physics Strategy

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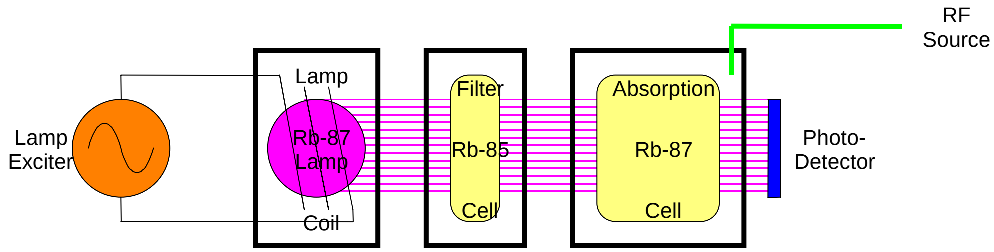
Conventional Rb Physics

- Requires resonant microwave cavity
- RF Discharge lamp *(1 Watt)*
- 3 (2?) cells, ovens, controllers

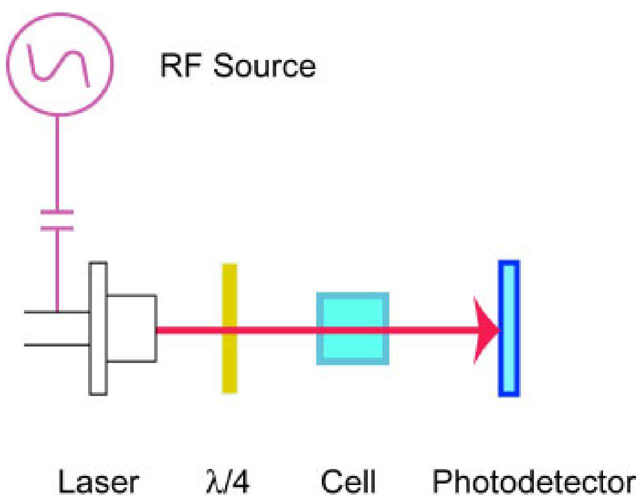


RF Discharge Lamp

Resonance Cell In Microwave Cavity

Coherent Population Trapping (CPT) Physics

- High-bandwidth Vertical-Cavity Surface Emitting Laser *(VCSEL)*
- Microwaves applied directly to VCSEL *(No cavity)*
- Potential for very small oven assembly



Ref. R. Lutwak et. al, Proceedings of the 33rd PTTI

The 10 mW Physics Package

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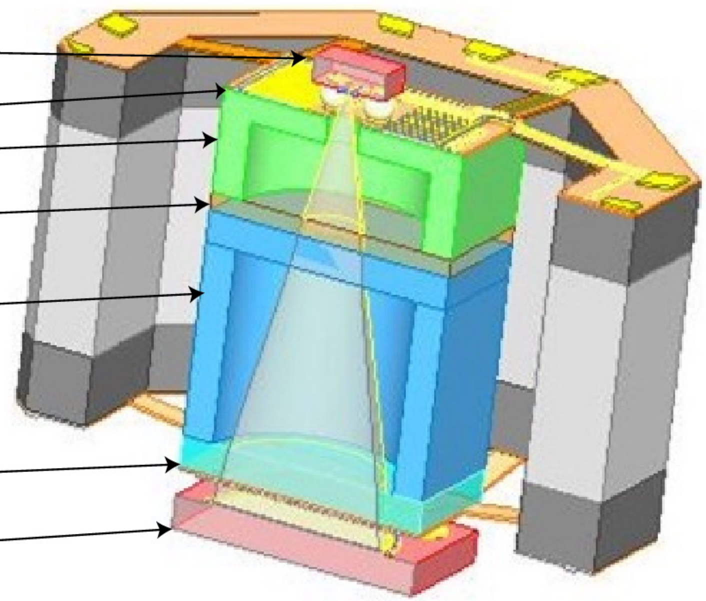
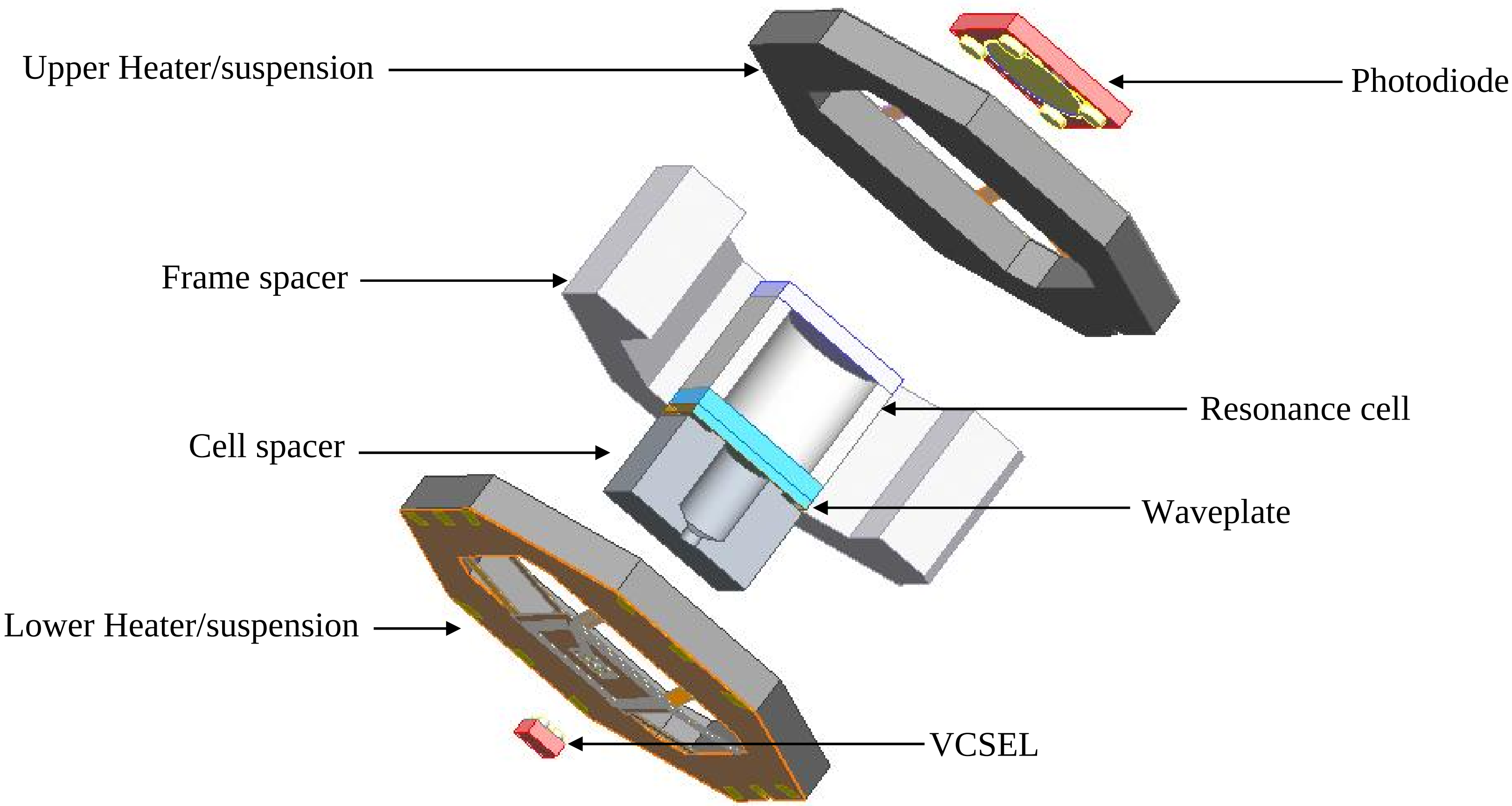


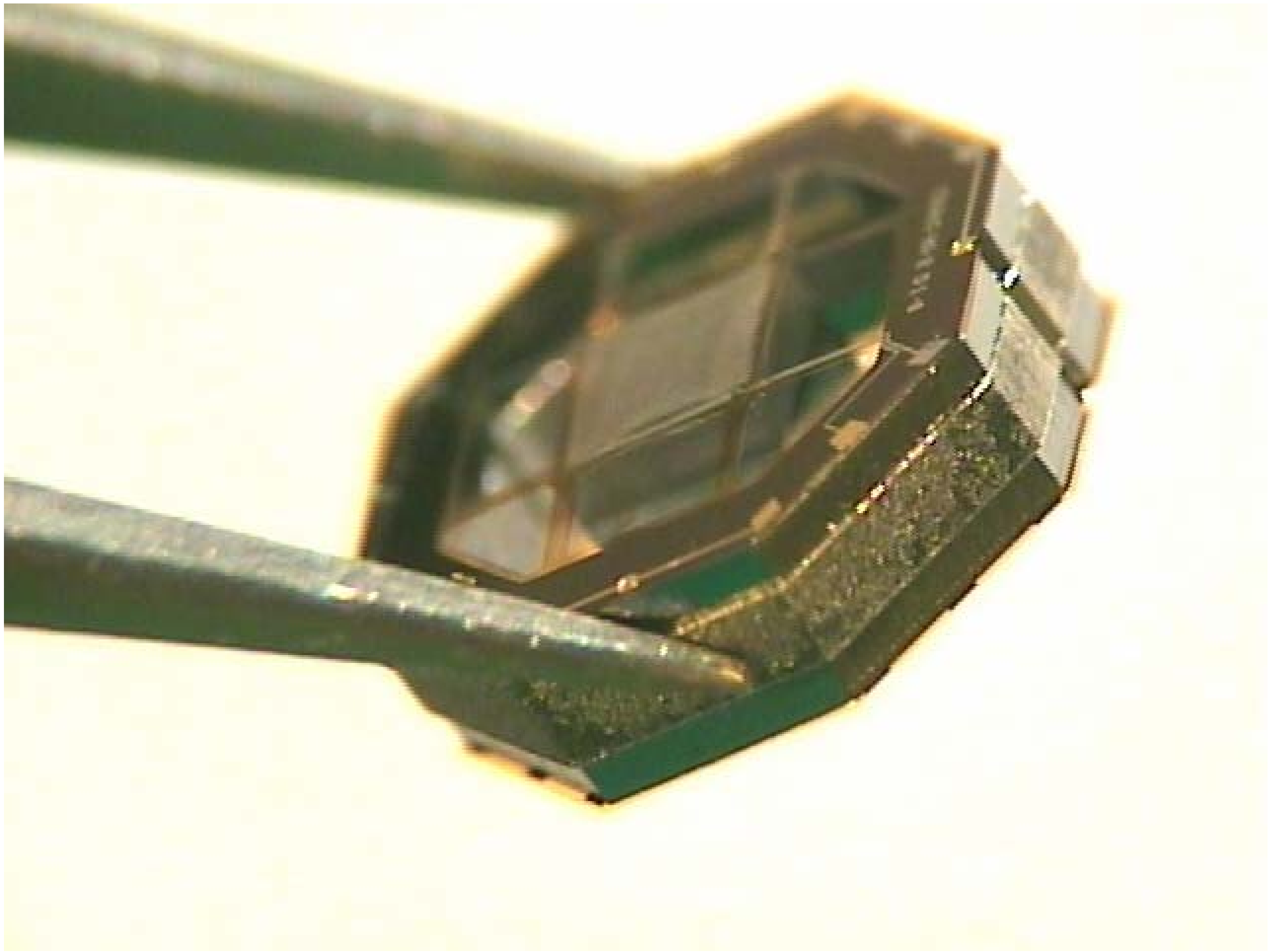
- Tensioned polyimide suspension
- Microfabricated Silicon vapor cell
- Low-power Vertical-Cavity Surface Emitting Laser (VCSEL)
- Vacuum-packaged to eliminate convection/conduction
- Overall Thermal Resistance 7000°C/W

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.

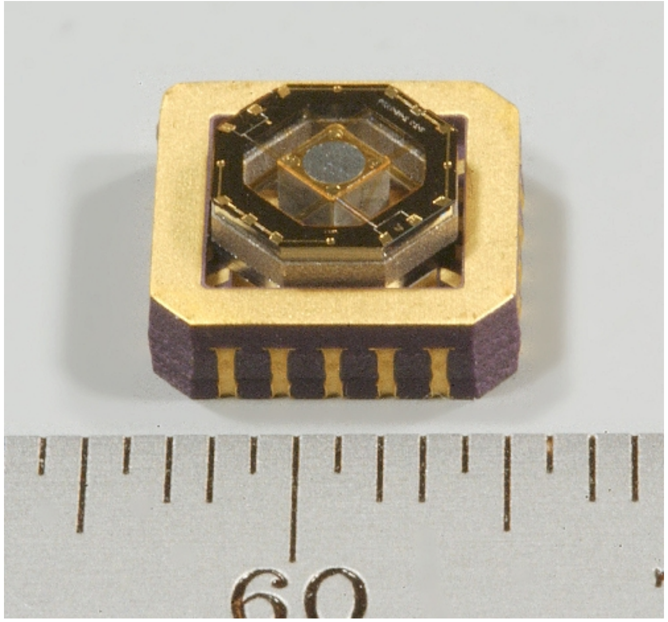
Physics Package Assembly



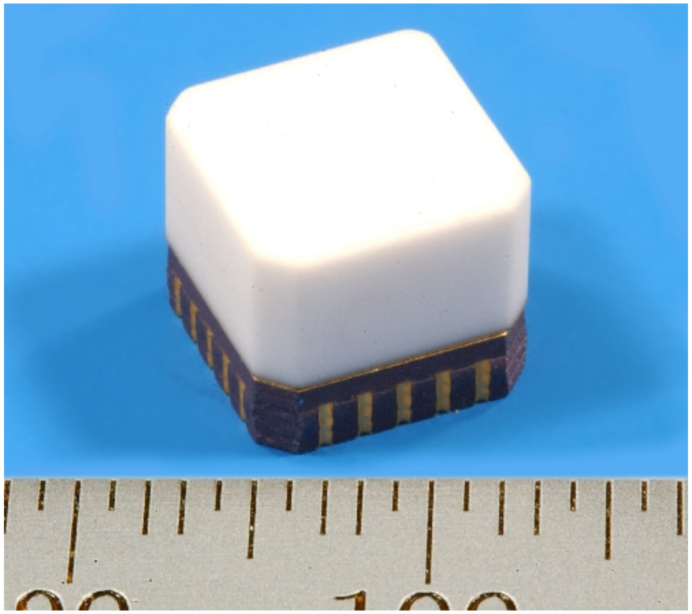
Physics Package



Physics Package in LCC



Physics package in LCC



Vacuum sealed

Physics Package Performance

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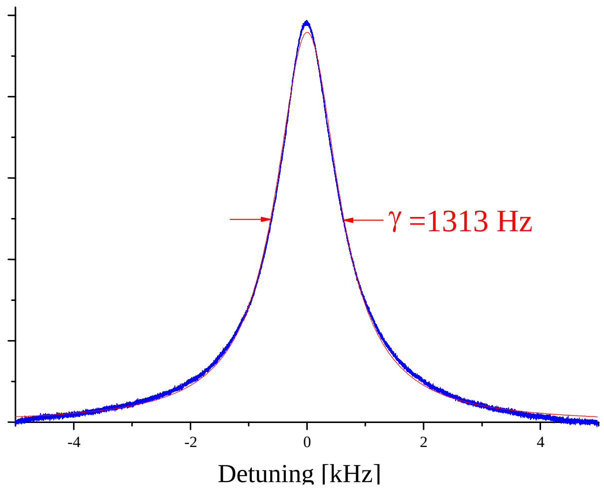
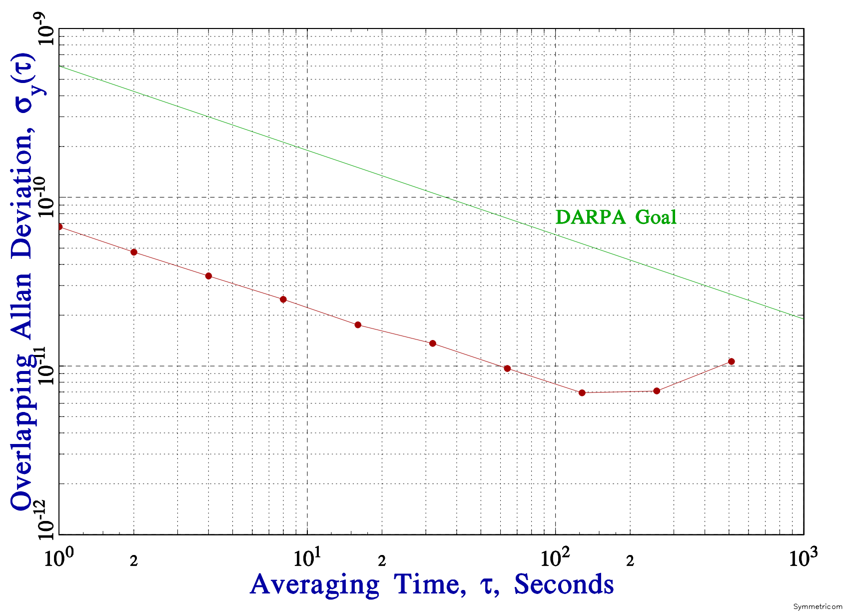
CPT Resonance @ 4.6 GHz



Resonance "Q" = 4×10^6

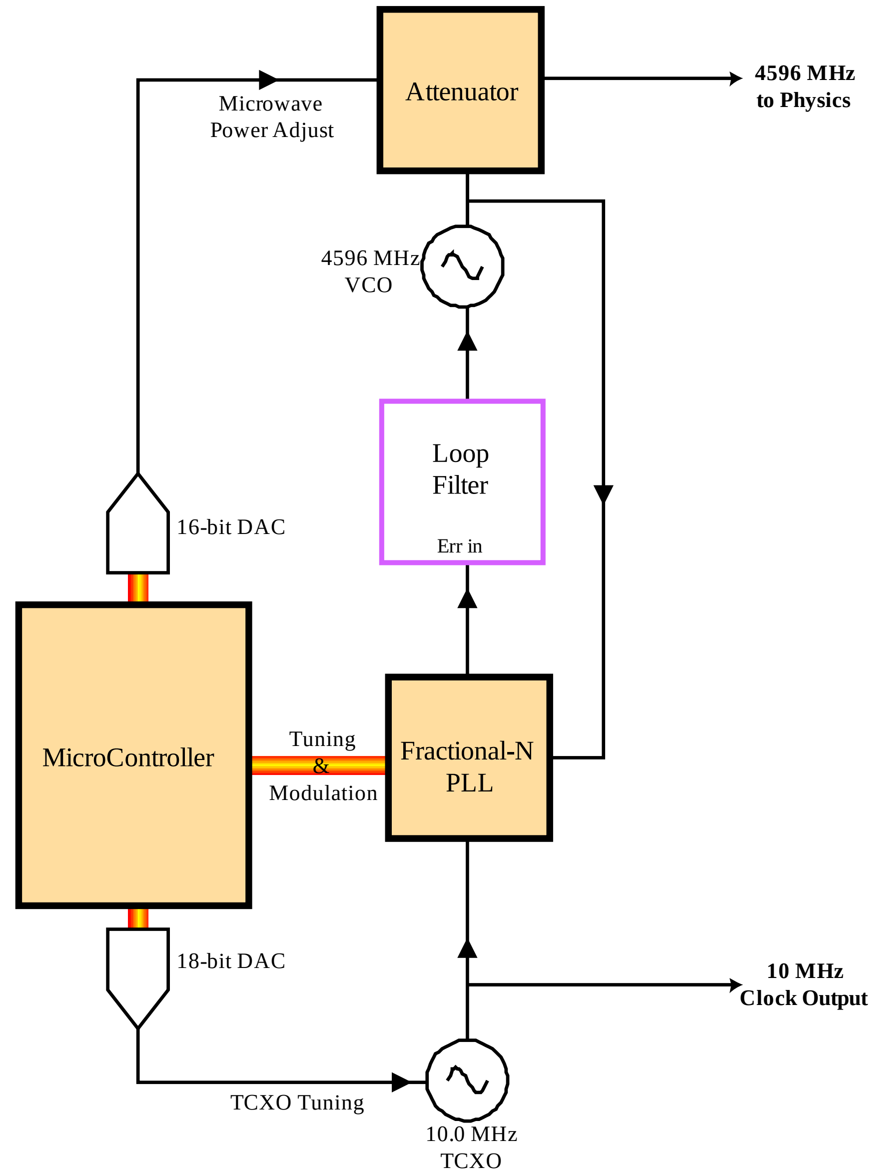
Stability vs. Time



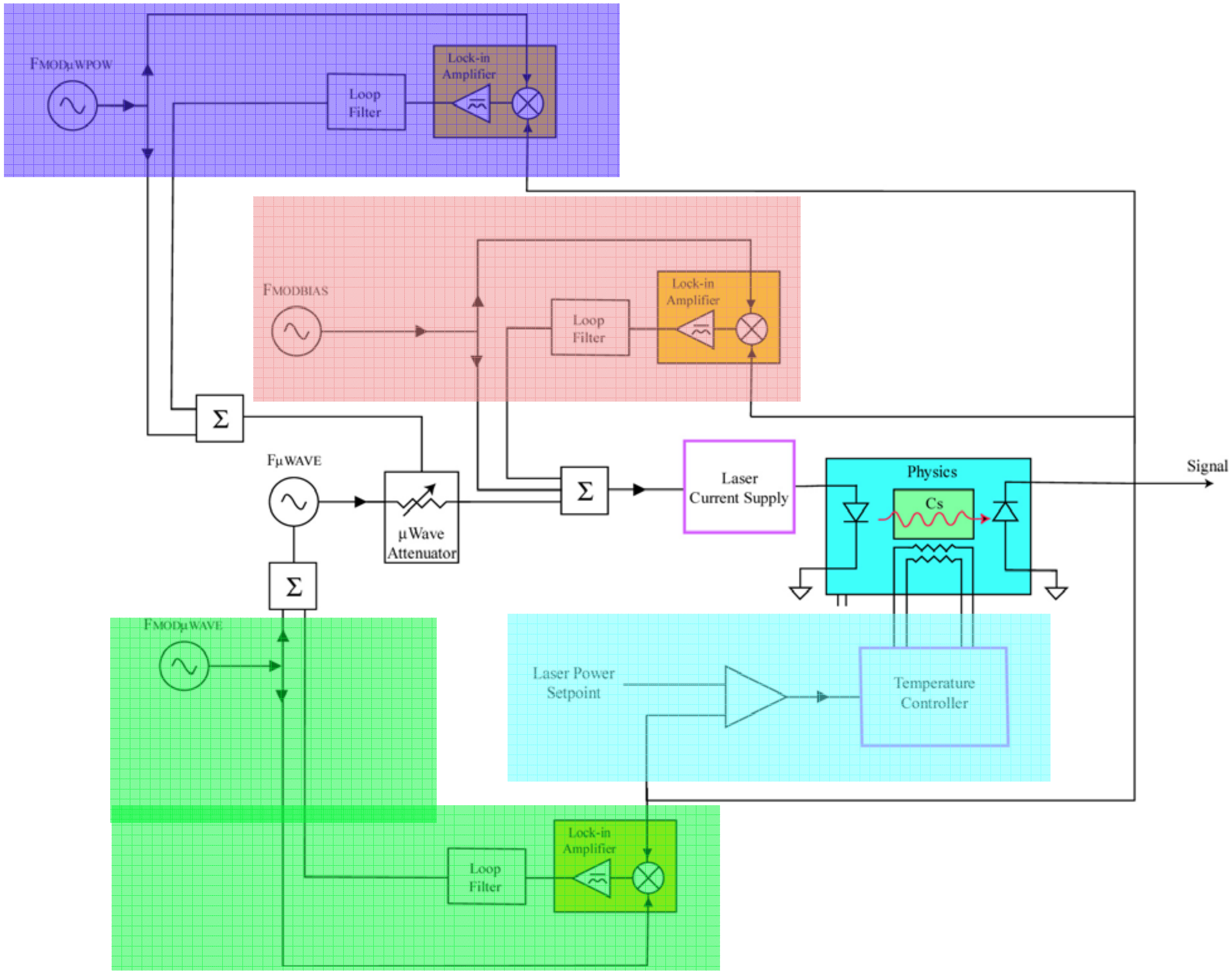
Microwave Synthesizer

- TCXO Output at 10 MHz
- Atomic Interrogation at 4596 MHz
- Fractional-N PLL
- Modulation via digital control of PLL
- Tuning via digital control of PLL

  Resolution: 2×10^{-12}



Control System



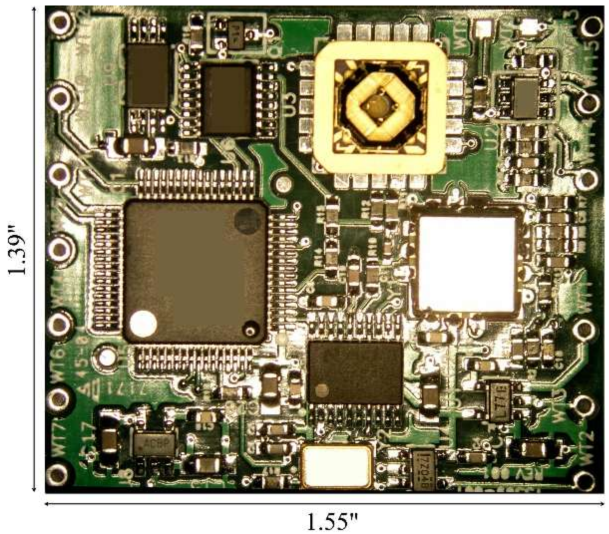
Laser Servo - Lock laser wavelength to optical absorption resonance via DC Bias

Temperature Servo - Optimize optical power via temperature

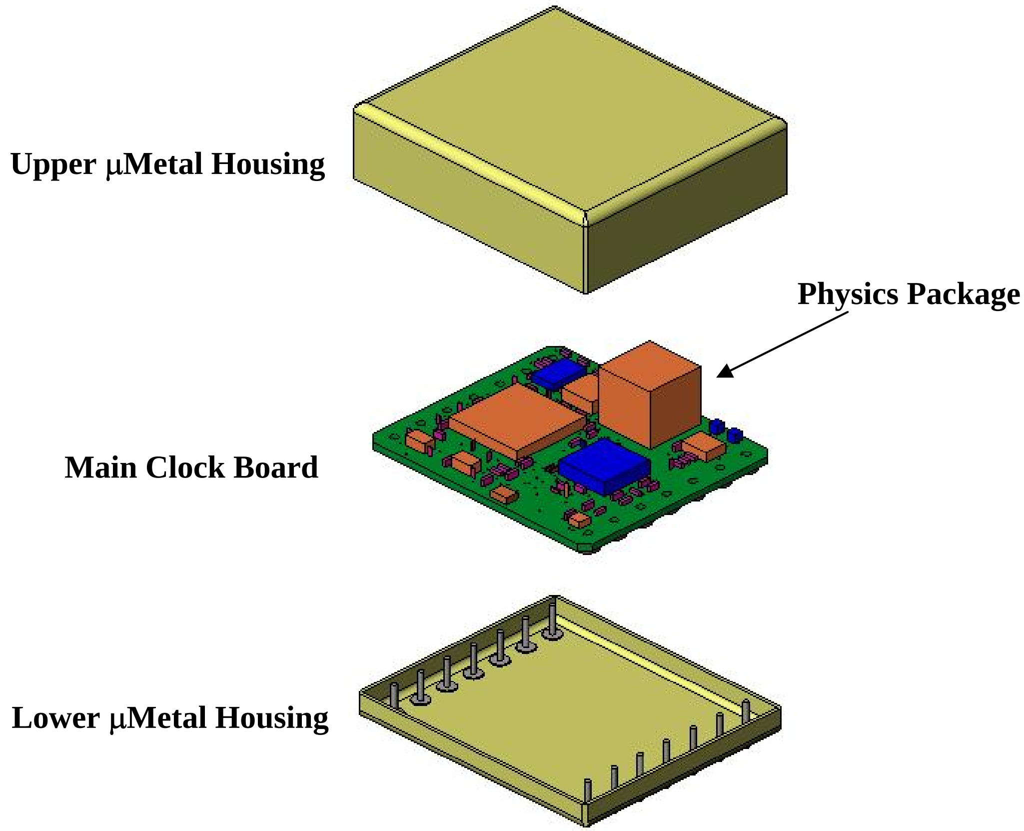
Clock Servo – Lock local oscillator to CPT resonance

Power Servo - Optimize CPT signal amplitude via µWave power

Control Electronics



Microwave System: 60 mW
Control System: 40 mW
Physics: 10 mW
Regulators & Passives: 15 mW
Total: 125 mW

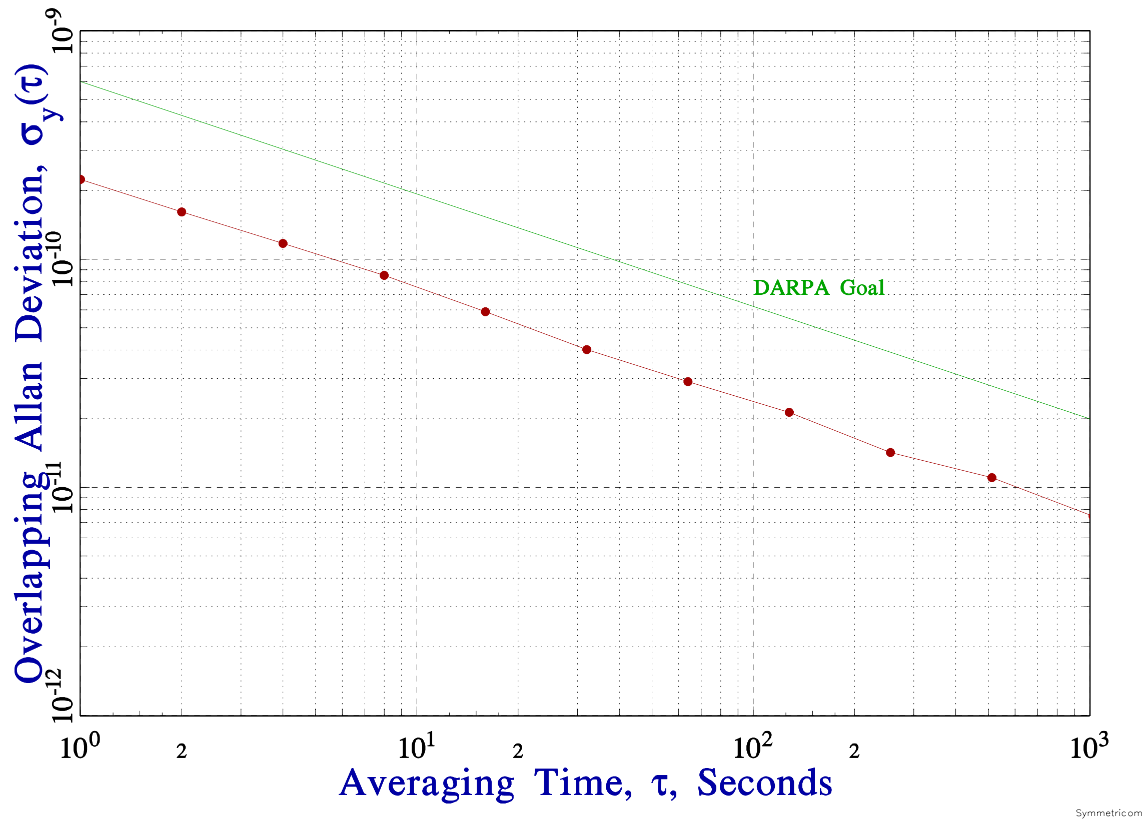


Typical Prototype Performance

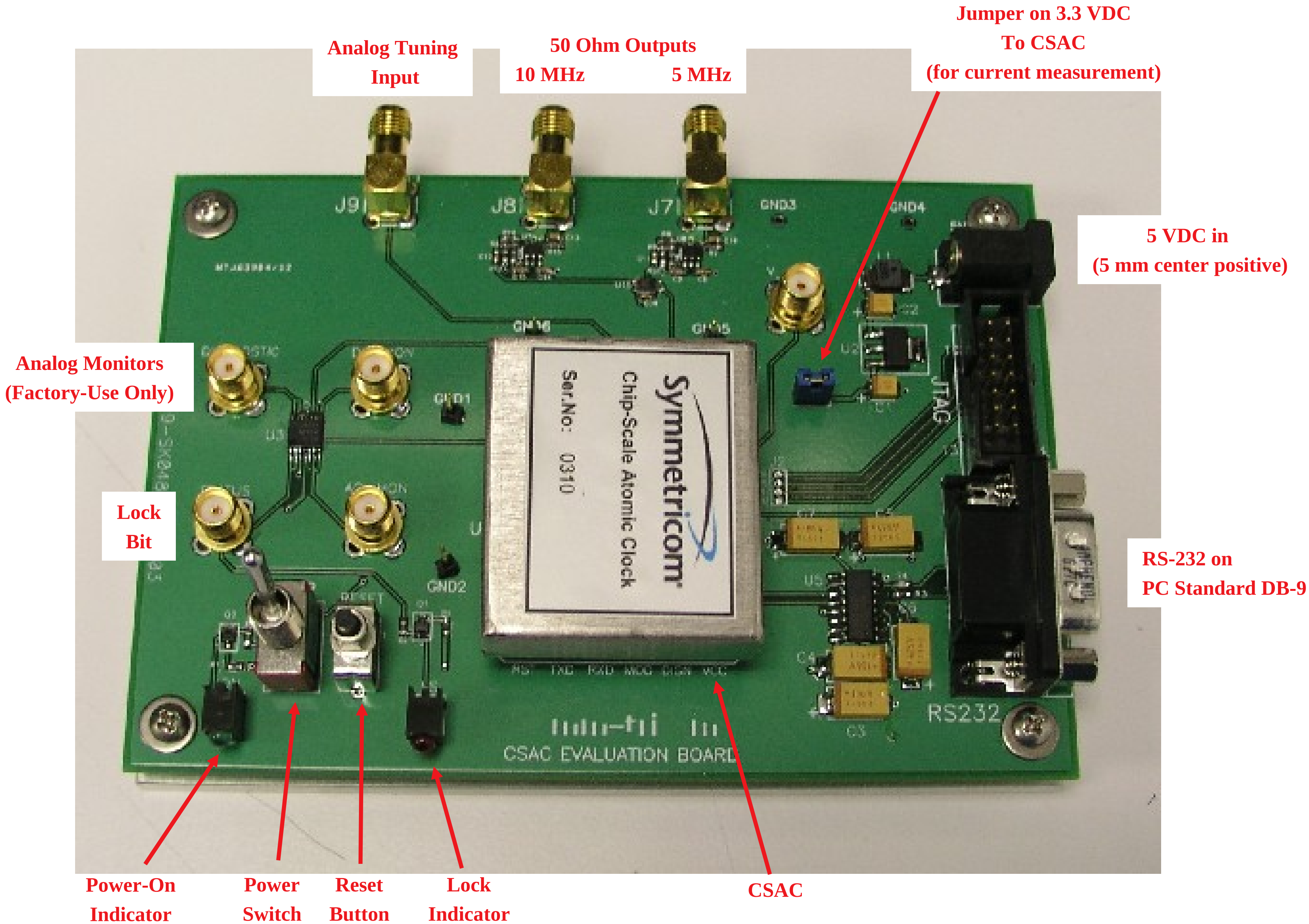
Size ≈ 15 cm^3

Power ≈ 125 mW

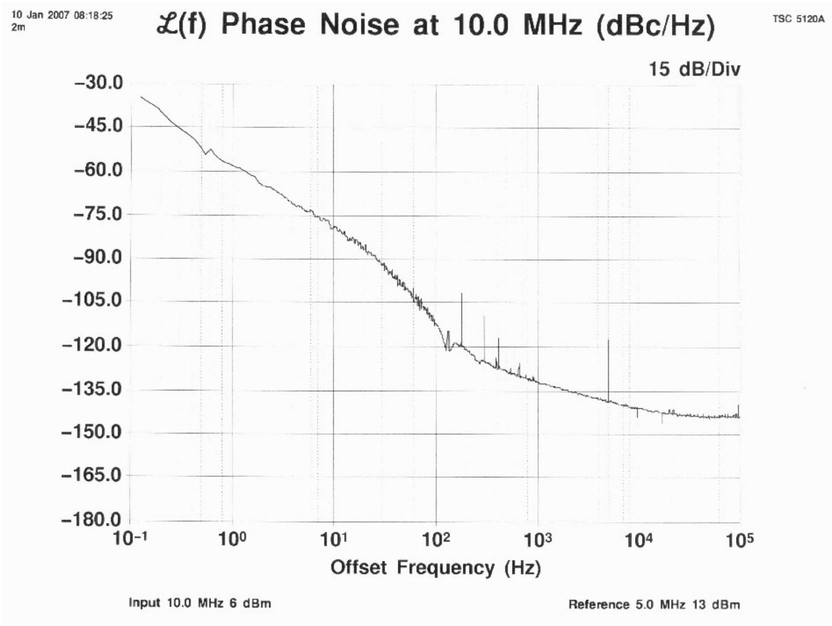
Stability ≈ 2-3 x10^{-10} $\tau^{-1/2}$

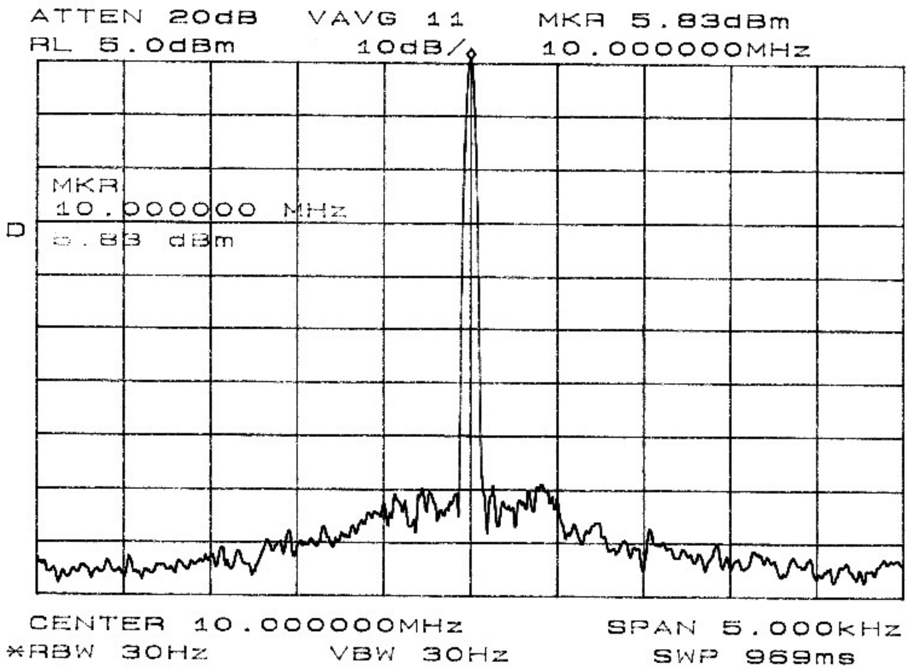


CSAC Prototype on Evaluation Board



10 MHz Clock Output



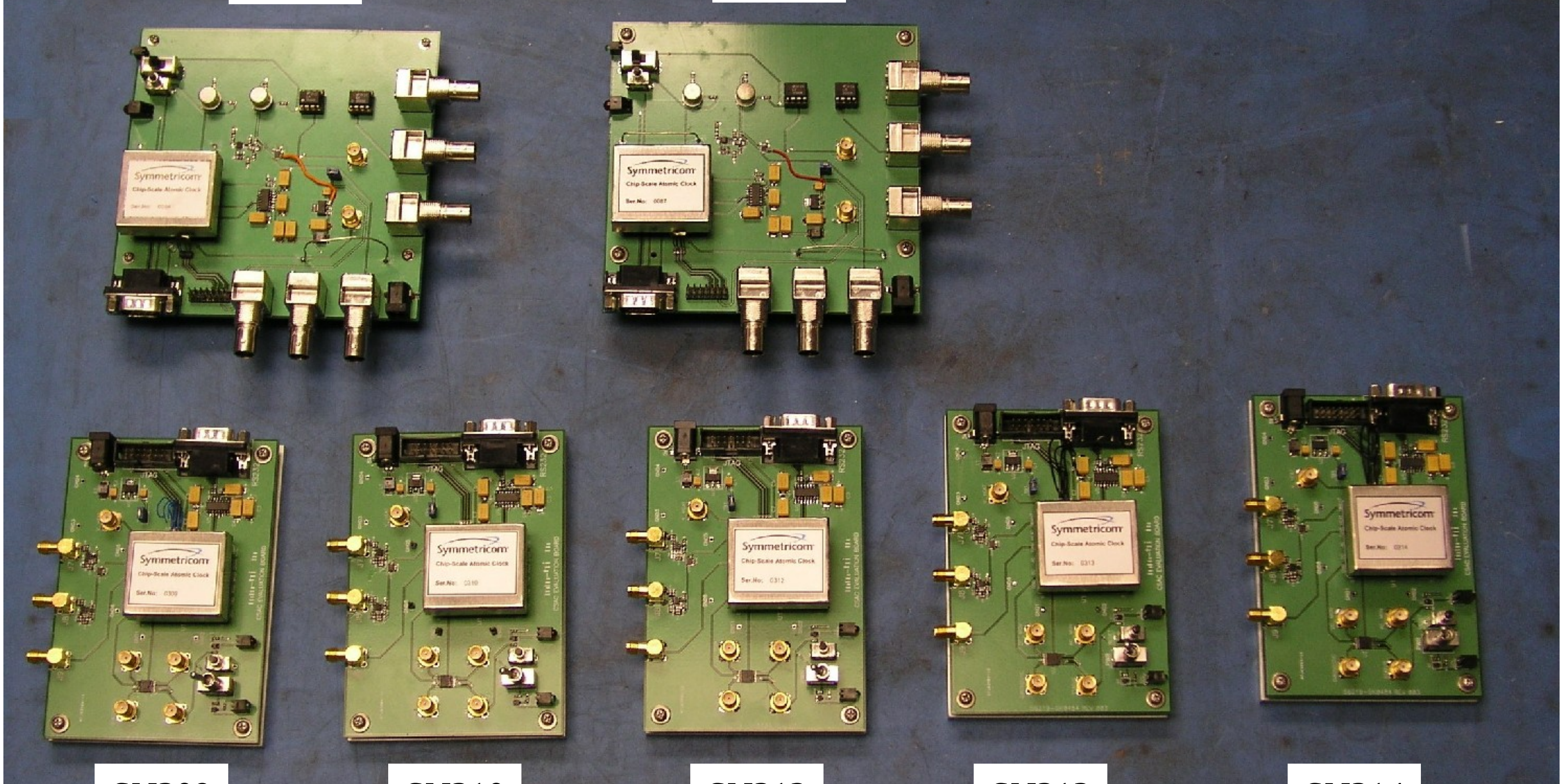


Short-Term Goals

1) Build and Test 10 Prototype Units
   - Measure long-term aging
   - Statistical variation of STS, TempCo, aging, retrace, etc.
   - Deliver to systems integrators and independent testing facilities
   - Support systems-level demonstrations
2) Reduce Size and Power
   - Develop smaller physics package
   - Develop low-power microwave oscillator
   - Test and incorporate lower-power active components

Prototype CSACs

SN084 SN087



SN309 SN310 SN312 SN313 SN314

Short-Term Stability

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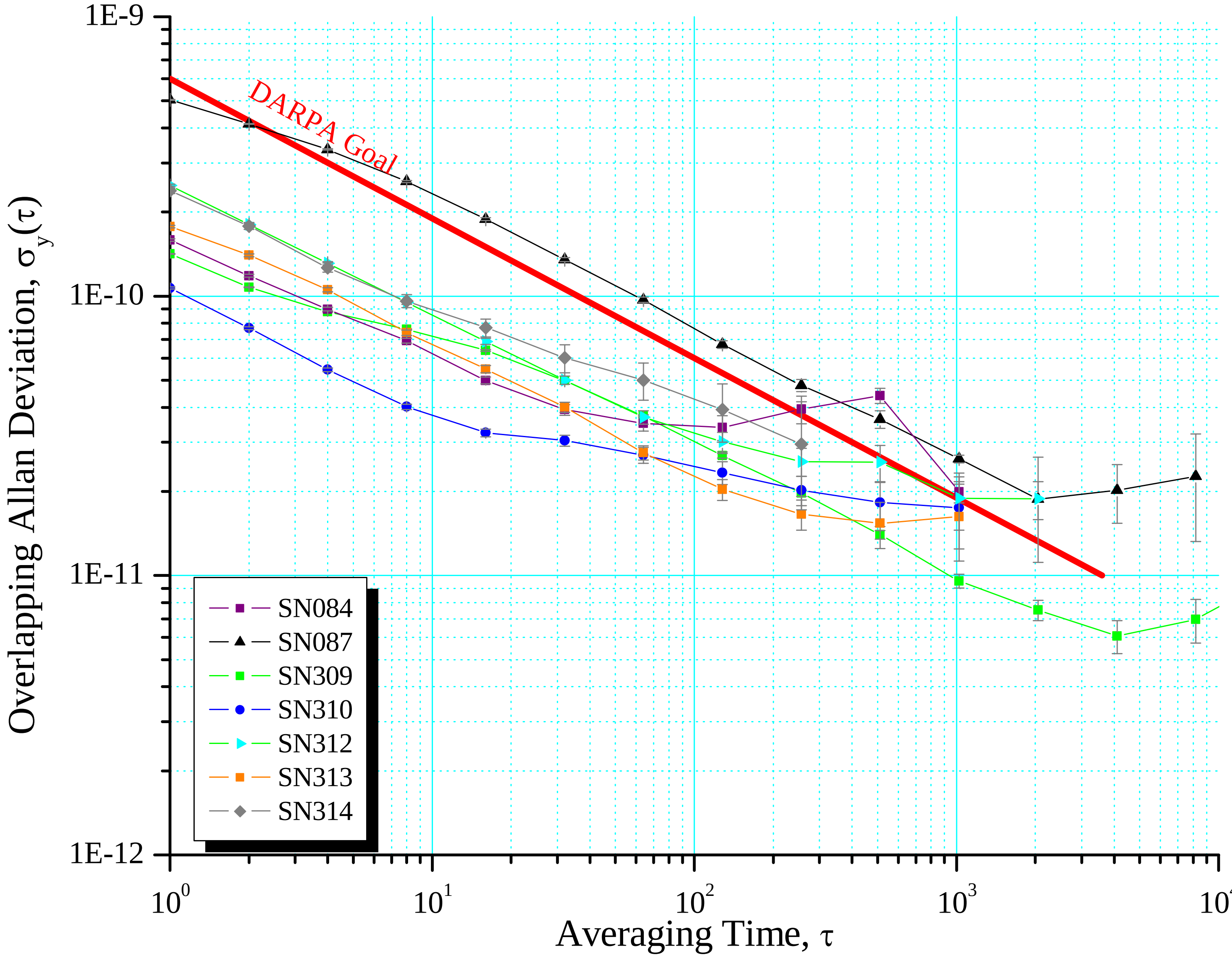

Evolutionary Path to 30 mW/1 cm^3

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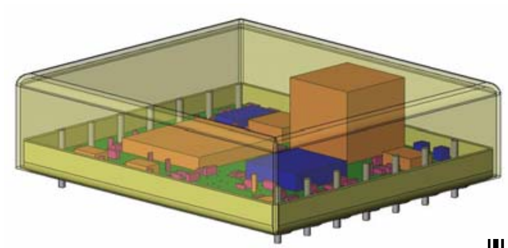
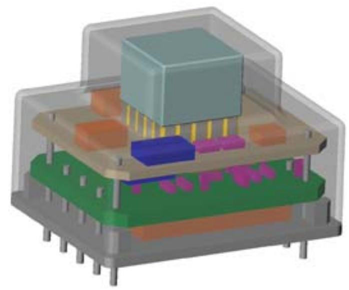
Current Prototype



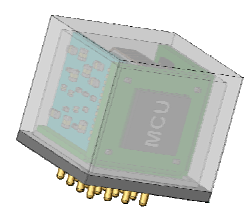
15 cm^3
125 mW

Small Low-Power Prototype



3 cm^3 *(including 0.35 cm^3 physics package)*
30 mW (4.6 GHz Output)
50 mW (10.0 MHz Output)

Tiny Micro-Power



1 cm^3
30 mW

4 cm^3 CSAC

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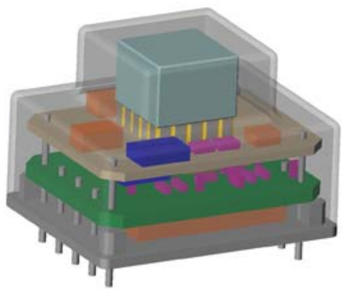
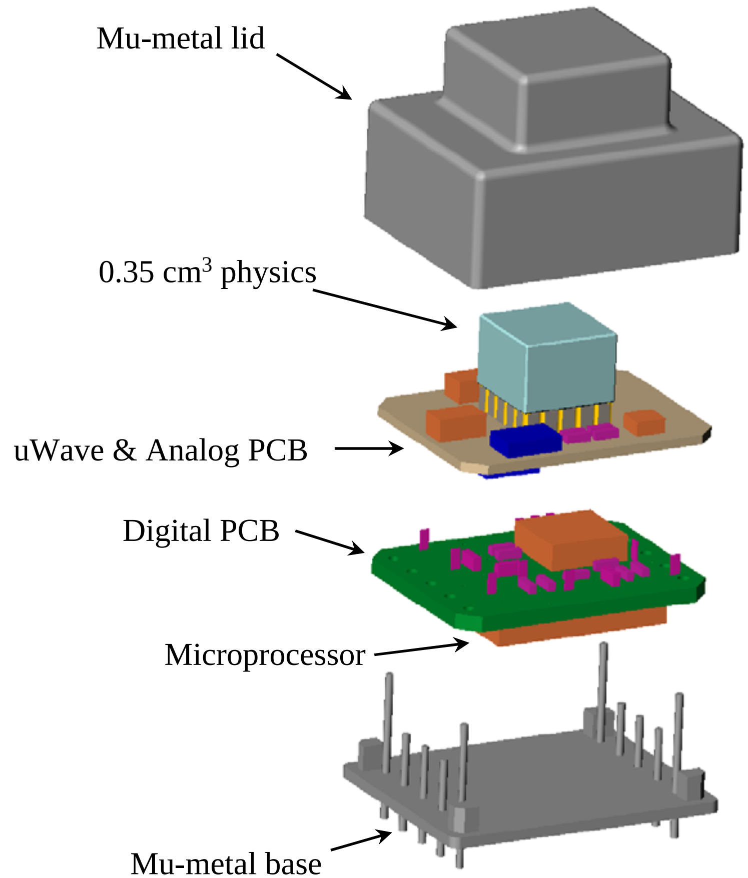
Small Low-Power Prototype



3.8 cm^3 *(including 0.35 cm^3 physics package)*

30 mW (4.6 GHz Output, no Vreg)

60 mW (10.0 MHz Output, Vreg)



4 cm^3

Prototype Concept

0.35 cm^3 Physics Package

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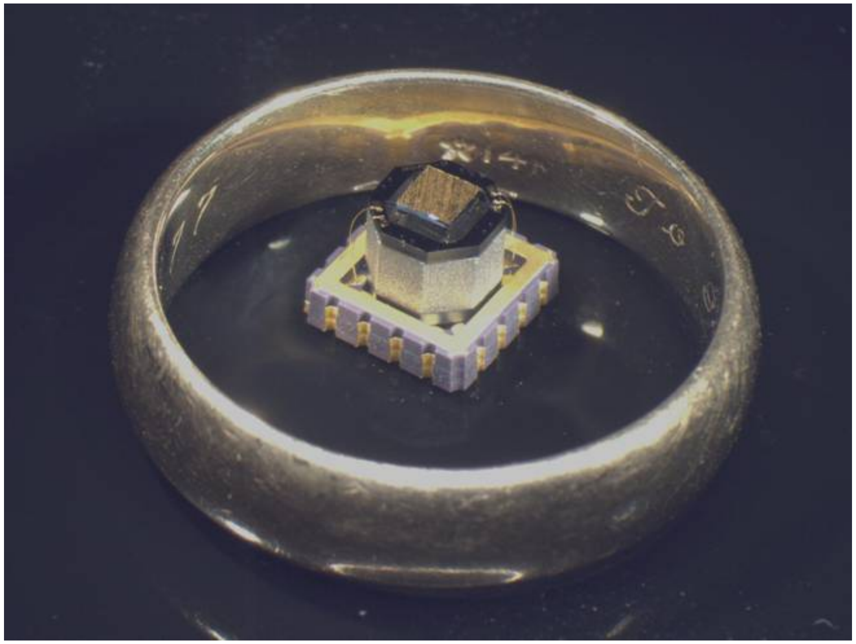

First prototype build 11/2006.

Demonstrated 85°C operation w/10 mW heater power

Fixture development underway

DRAPER LABORATORY