Jet Propulsion Laboratory
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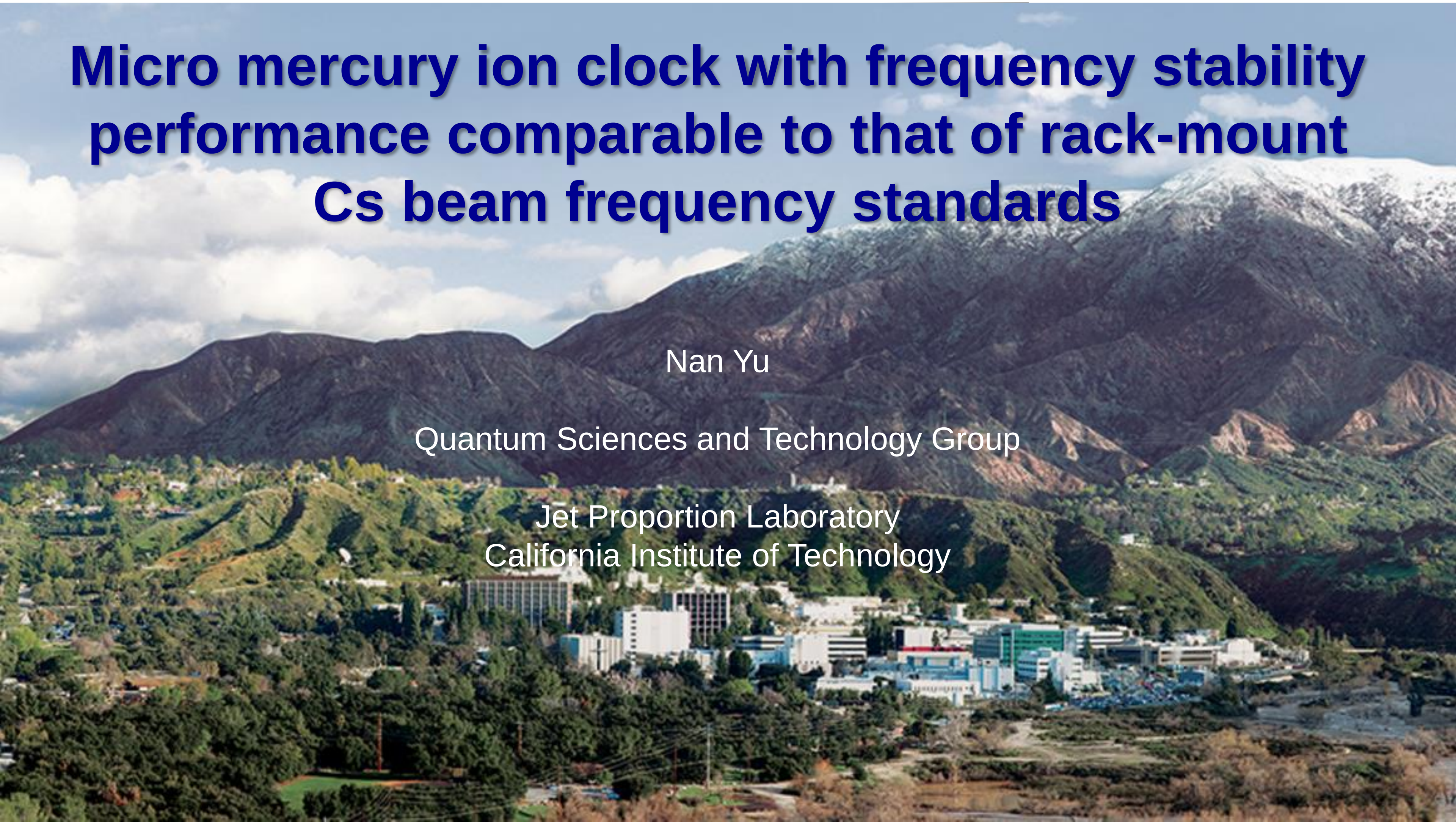

Micro mercury ion clock with frequency stability performance comparable to that of rack-mount Cs beam frequency standards

Nan Yu

Quantum Sciences and Technology Group

Jet Proportion Laboratory
California Institute of Technology

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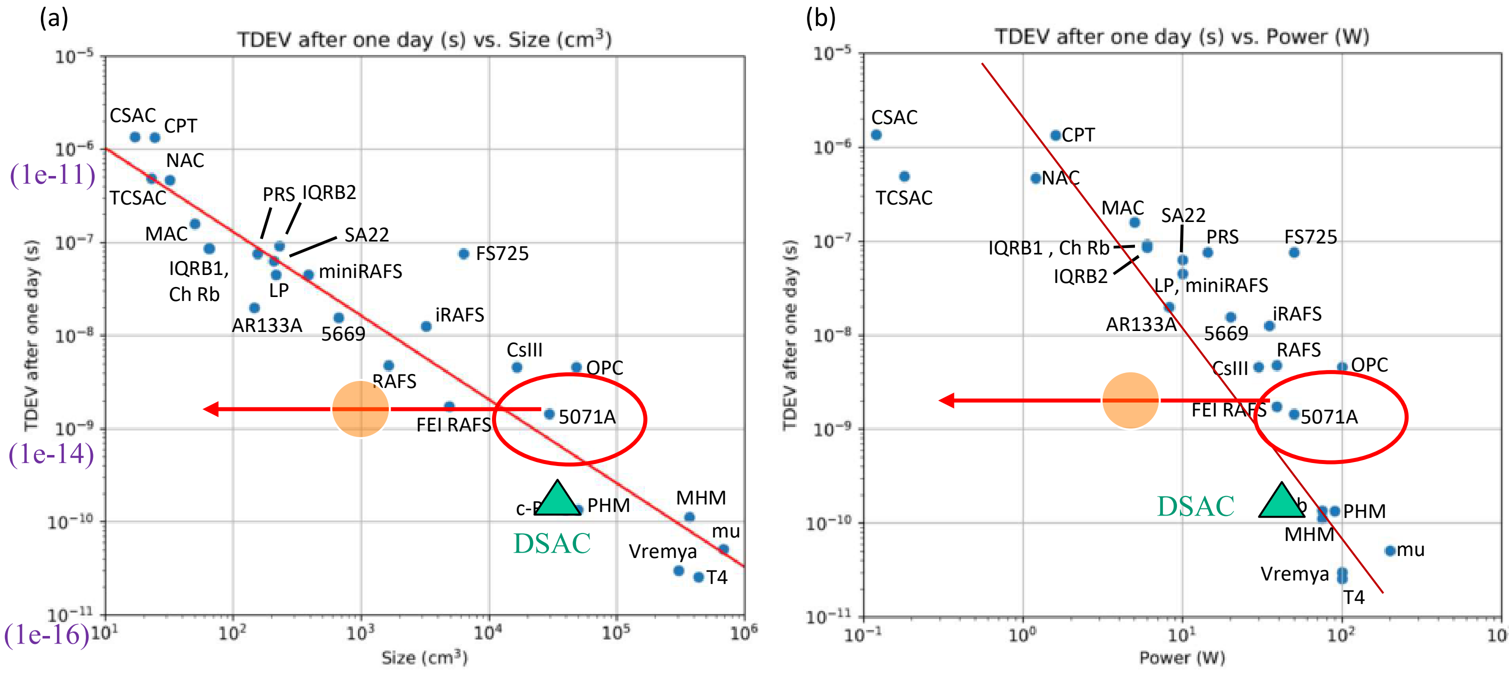
Compact Atomic Frequency Reference Standards – State of Practice

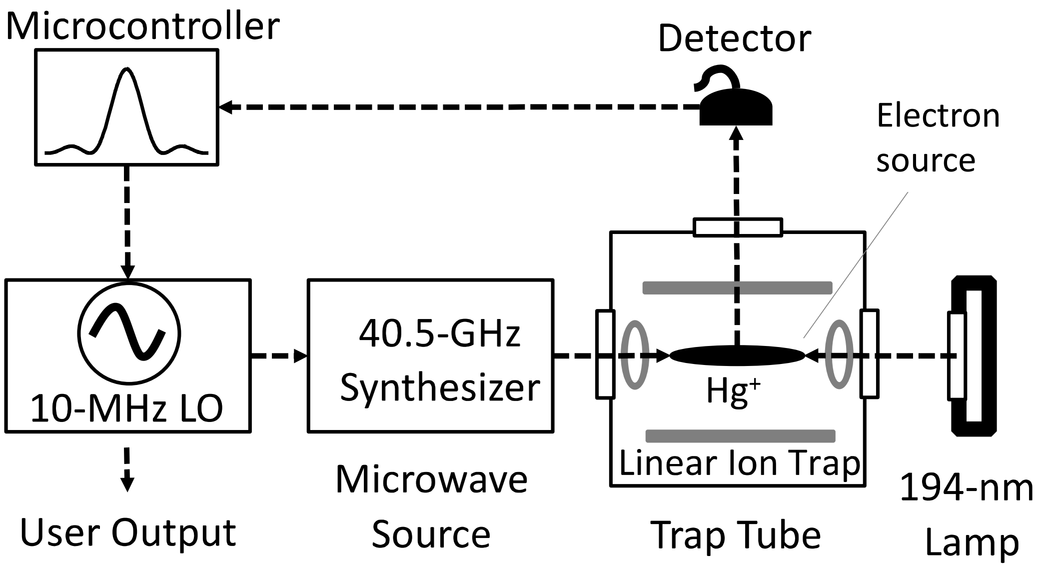


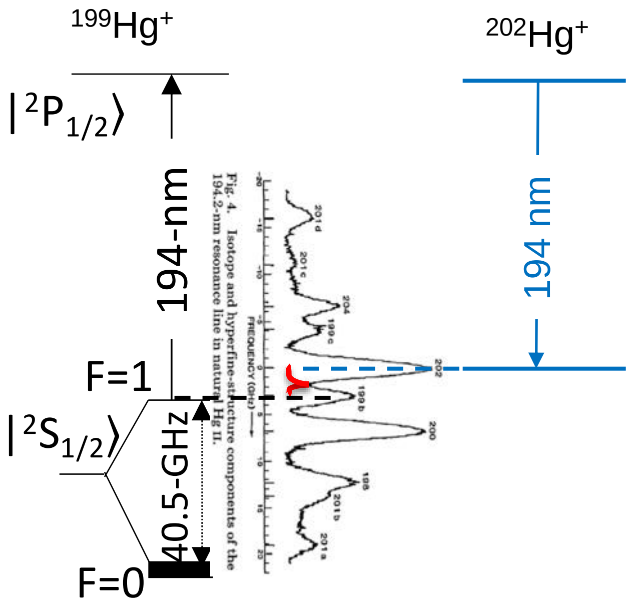
Legend
CSAC = Microchip SA.45s CSAC
TCSAC = Teledyne CSAC (preliminary)
CPT = Chengdu Spaceon CPT
NAC = Accubeat Rb NAC1
IQRB1 = IQD IQRB-1
Ch Rb = Chengdu Spaceon XHTF1031
MAC = Microchip SA.35m
SA22 = Microchip SA.22c
PRS = SRS PRS10
LP = Spectratime low profile Rb
AR133A = Accubeat AR133A Rb
miniRAFS = Spectratime miniRAFS
IQRB2 = IQD IQRB-2
5669 = FEI FE-5669 Rb
FS725 = SRS FS725
RAFS = Excelitas space RAFS
iRAFS = Spectratime iSpace RAFS
CsIII = Microchip CBT 4310B CsIII
FEI RAFS = FEI RAFS
5071A = Microchip 5071A CBT
OPC = Chengdu Spaceon TA1000 OPC
c-Rb = Spectradynamics cold Rb c-Rb
PHM = T4Science pHMaser 1008
mu = Muquans cold-atom MuClock (preliminary)
MHM = Microchip MHM 2010 H Maser
Vremya = Vremya VCH-1003M H Maser
T4 = T4Science iMaser-3000 H Maser

● Micro Mercury Trapped Ion Clock (M2TIC)

Marlow, B. L. S. & Scherer, D. R. A review of commercial and emerging atomic frequency standards. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 68, 2007–2022 (2021).

Basic Mercury Ion Clock Scheme





Advantages of using Hg ions as atomic reference

- No lasers
- No microwave cavity
- No oven
- Low *g* sensitivity
- Low *B* field sensitivity

Cutler, L. S., Giffard, R. P. & McGuire, M. D. A trapped mercury 199 ion frequency standard. In Proceedings of the 13th Annual Precise Time and Time Interval Systems and Applications Meeting 563–578 (1981).

"Integrated physics package of micromercury trapped ion clock with -10^-14 level frequency Stability," T. Hoang *et al*., Appl. Phys. Lett. 119, 044001 (2021); https://doi.org/10.1063/5.0049734.

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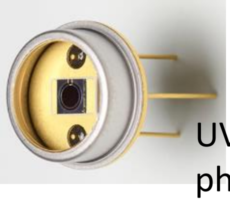
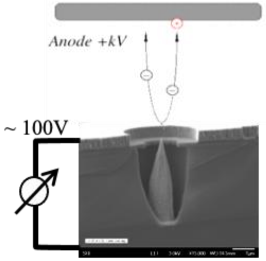
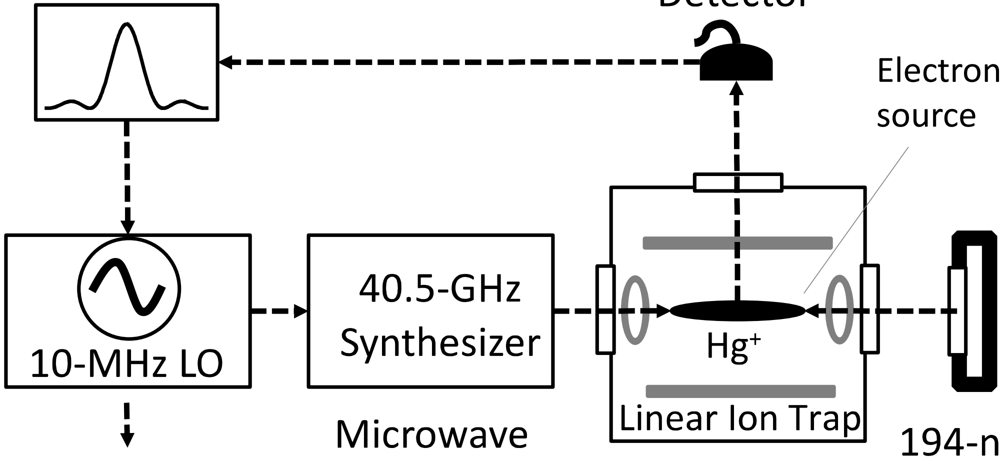
SWaP Reduction Approaches in Hg+ Clock



UV single photon APD??



Spindt Cathode ✓



Microcontroller

Detector

Electron source

10-MHz LO

User Output

40.5-GHz Synthesizer

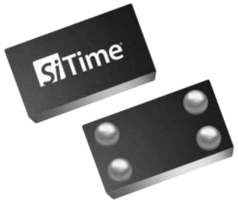
Microwave Source

Hg$^+$

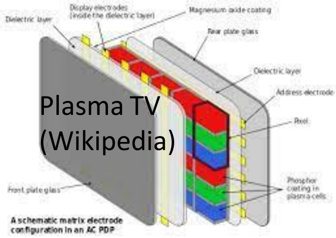
Linear Ion Trap

Trap Tube

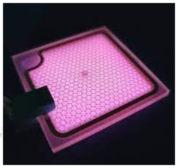
194-nm Lamp



Ultra-low power oscillator??

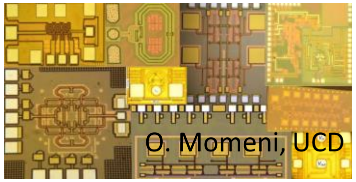


Plasma TV (Wikipedia)



Lighting industry

Micro discharge lamp?? ✓



O. Momeni, UCD

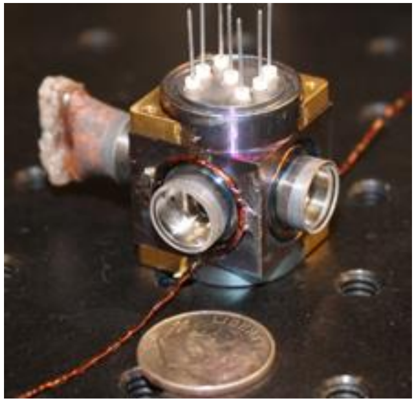
High speed CMOS Electronics? ✓

DARPA IMPACT Trap PKG: 3 cc

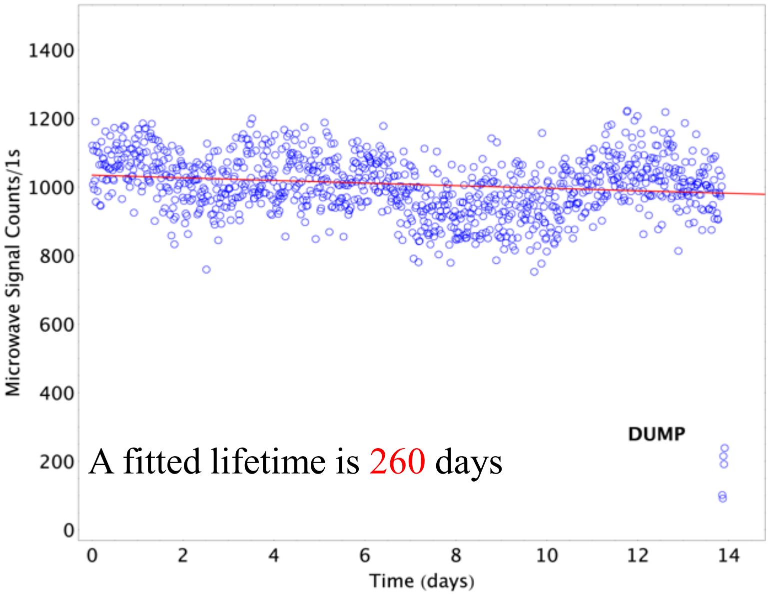
Yb+ micro tube ✓

Micro Mercury Ion Trap Tube

- Trap vacuum tube fabricated using the glass-metal seal approach.
- Sapphire windows, DUV transmission, impermeable to helium.
- Constructed from materials to withstand bake-out to 400 ˚C.
- Use of field emission electron (FEA) source.
- Non-evaporative getter to maintain high vacuum.
- Helium buffer gas

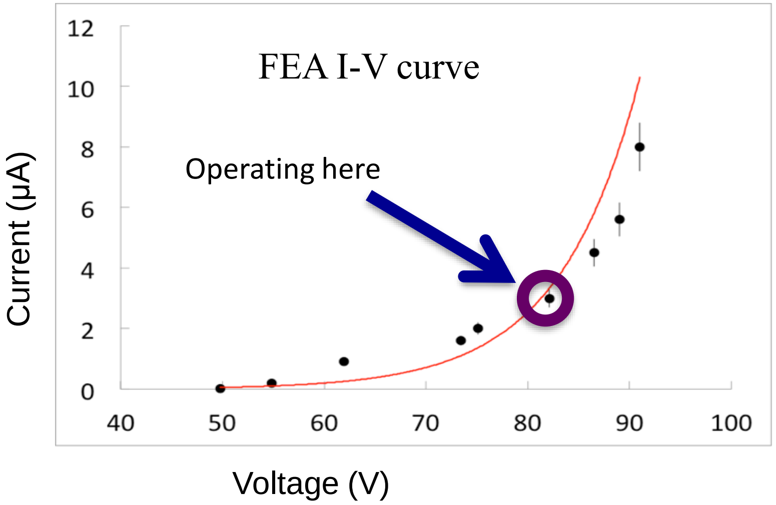


U3.1 sealed tube has been working over 4 years without any sign of degradation



A fitted lifetime is 260 days

The actual lifetime may be well > 260 days.



FEA I-V curve

Operating here

<10 mW DC power, normally operate infrequently.

"Integrated physics package of micro mercury trapped ion clock with -10^-14 level frequency Stability," T. Hoang *et al.*, Appl. Phys. Lett. 119, 044001 (2021); https://doi.org/10.1063/5.0049734.

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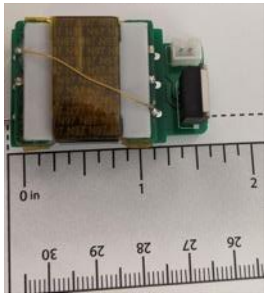
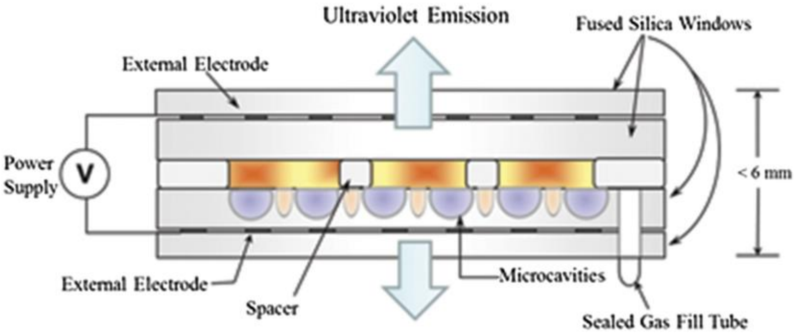
194 nm DUV Micro Plasma Discharge Lamp

- The dielectric barrier micro cavity plasma discharge lamp design.
- Helium carrier gas provides transient excited He dimers for efficient one-step Hg ion excitation and 194 nm generation.
- Pulsed high voltage plasma excitation for intense efficient light production.

Mercury micro discharge lamp

Lamp driver

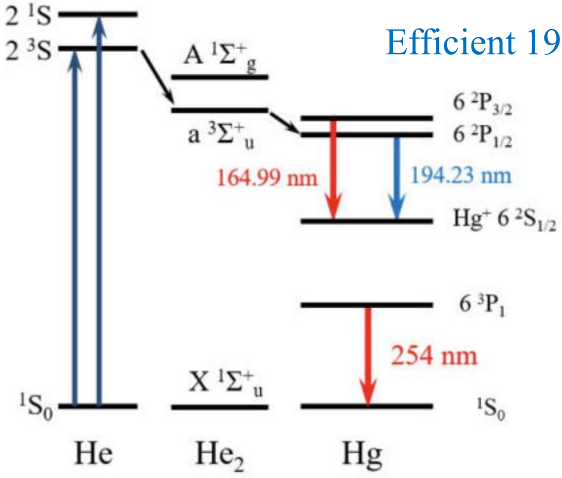


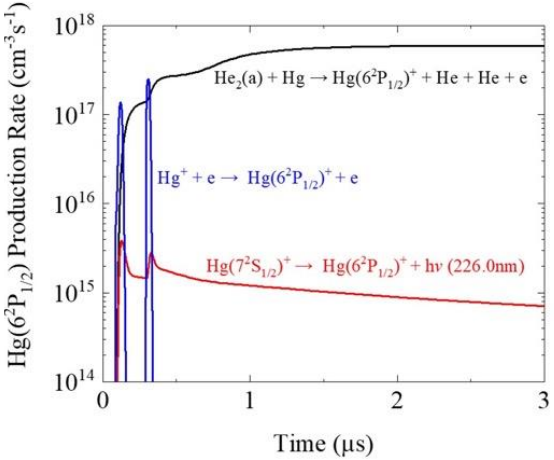


Micro plasma discharge concept

S.-J Park, *et al*. 2016 IEEE International Conference on Plasma Science (ICOPS) 1–1 (IEEE, 2016).

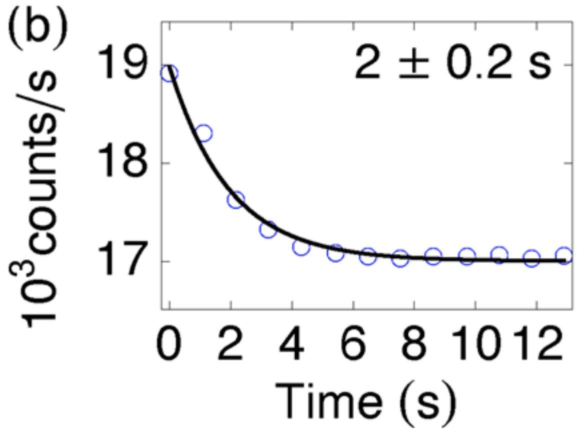
Efficient 194 nm generation mechanism





S. Park, *et al.* Plasma Sourc. Sci. Technol. 31, 045007 (2022).

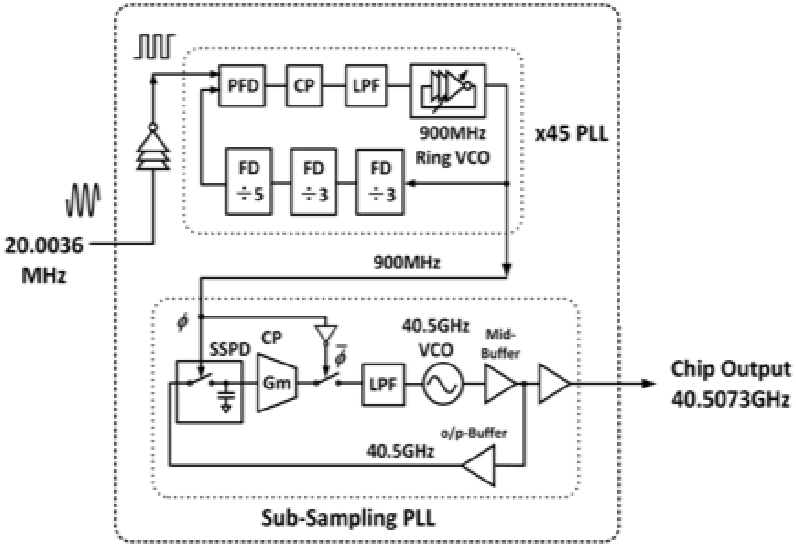
Optical pumping time

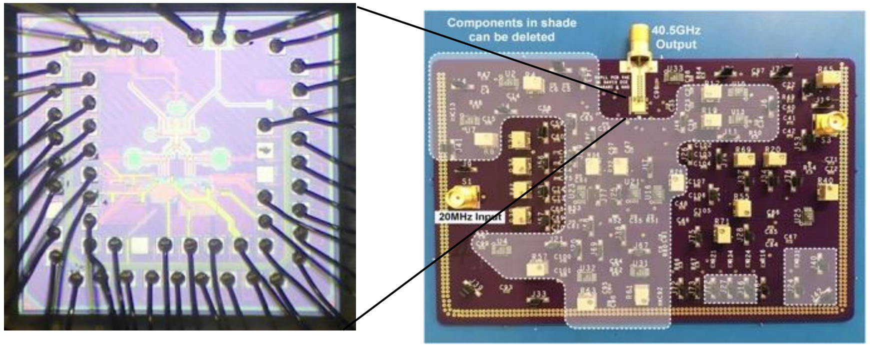


Sub-second pumping time has been demonstrated with **300 mW** DC power

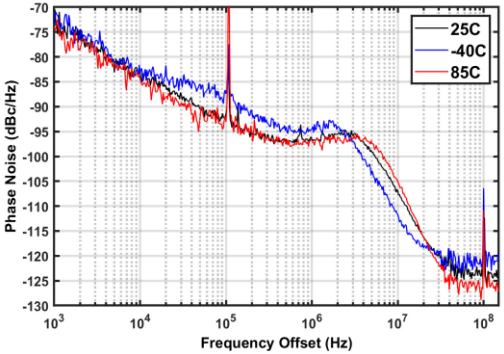
Lower Power Low Noise 40 GHz Synthesizer

- High-speed CMOS circuitry for overall low power consumption
- Sub-sampling phase detector for dividerless loop resulting low power and low noise
- Dual PLL architecture for robust locking operation with minimum power consumption.
- Temperature compensation and wide tuning range for wide operating temperature range





~ 40 mW power consumption
8 mW on the chip



Chip temperature locking range

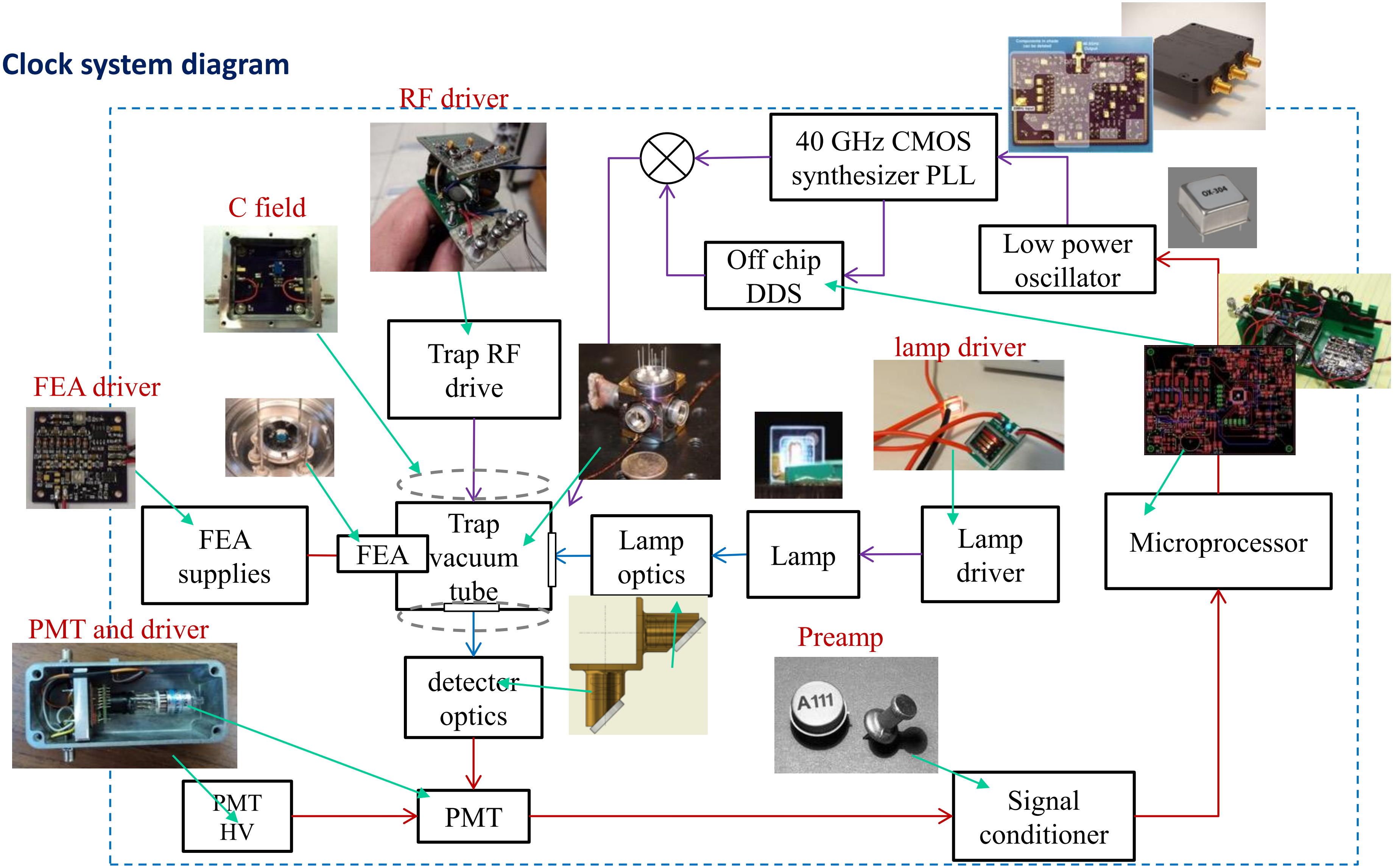
The second generation CMOS synthesizer board (40.5 GHz output phase locked to 20 MHz input)

Wang, H. & Momeni, O.. In 2019 IEEE Radio Frequency Integrated Circuits Symposium (RFIC) 171–174 (IEEE, 2019).

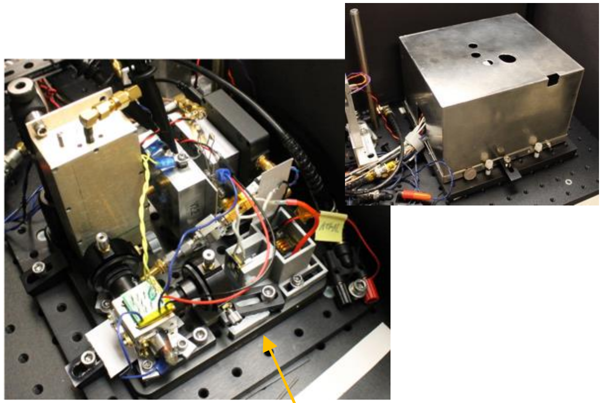
Wang, H. & Momeni, O. IEEE Trans. Microw. Theory Tech. 69, 469–481 (2021).

Micro Mercury Ion Clock Components

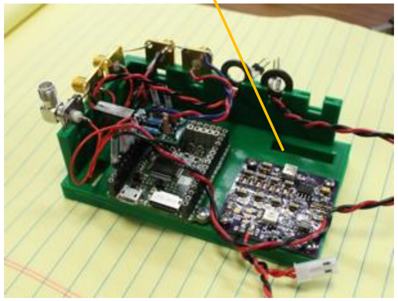
Clock system diagram



Evaluation of Integrated Clock Stability Performance

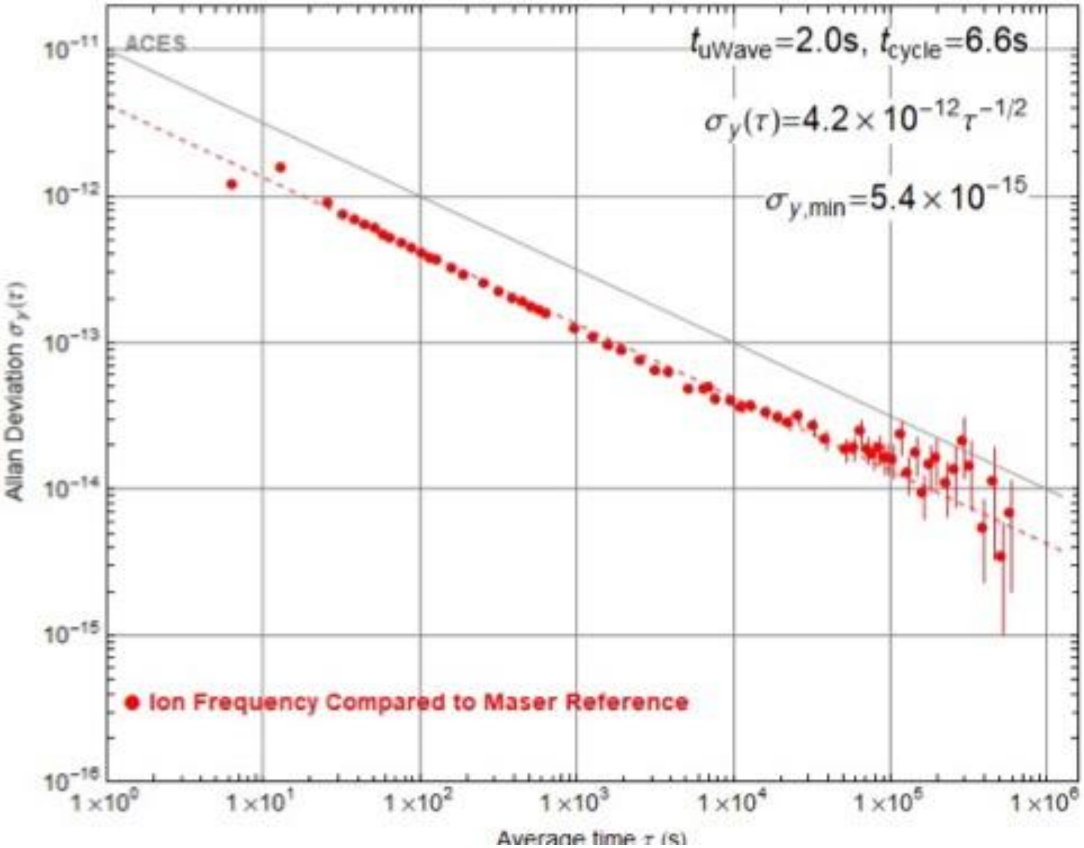


M2TIC U3.1



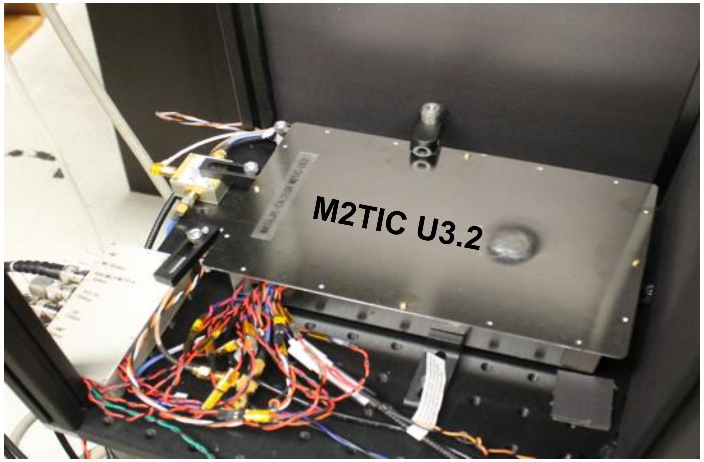
COTS processor controller

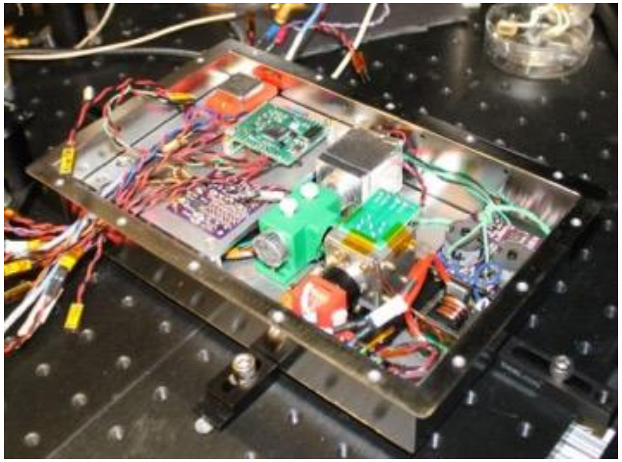
Measurements of the trapped ion stabilities against a hydrogen maser.

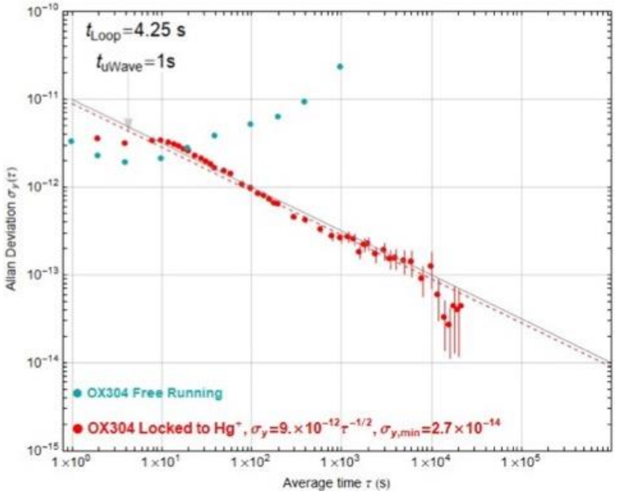


- U3.1 is a working breadboard prototype and has been used for all other component tests.
- Short-term instability capable of $< 4 \times 10^{-12}\tau^{-1/2}$, depedent on interrogation time.
- Demonstrated the ion reference a long-term fractional frequency instability to $< 6 \times 10^{-15}$.
- Estimated drift rate at 1×10^{-15}/day

Integrated Clock Packages







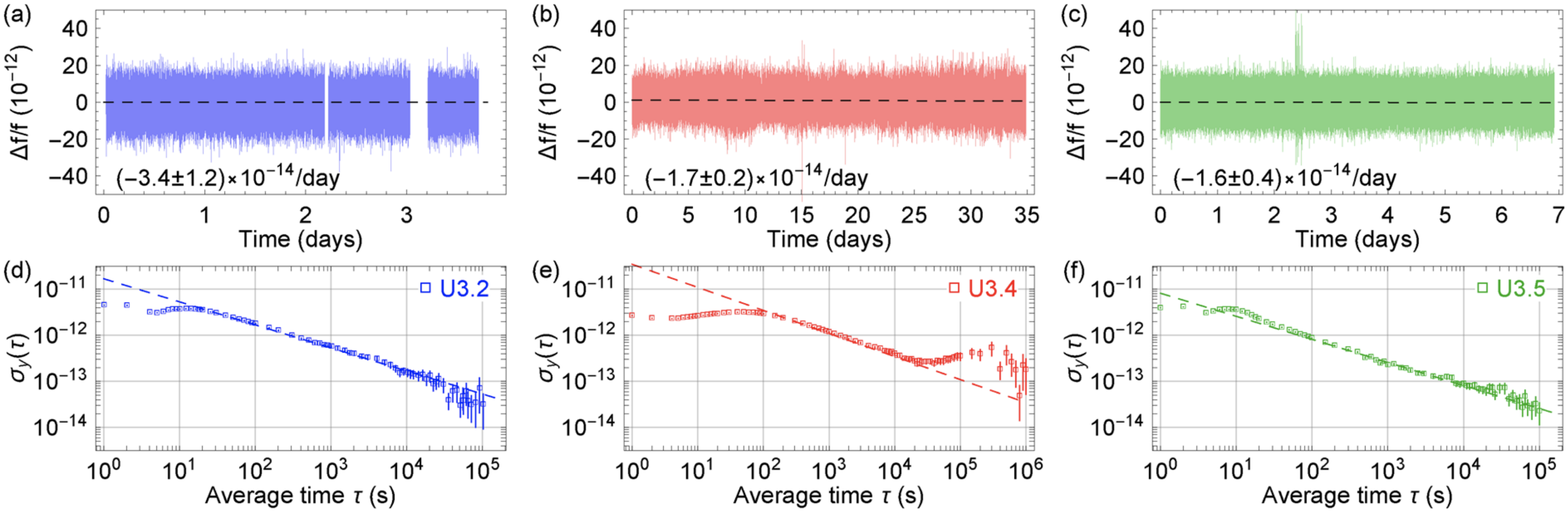
Frequency stability performance measured at JPL.

A total of three standalone prototypes are built.
SWaPs and Performances at JPL

Prototype	U3.2	U3.4	U3.5
Size	1.1 L	1.1 L	1.1 L†
Weight	1.2 kg	1.2 kg	1.2 kg†
Power	4.6 W	4.6 W	5.9 W
$\sigma_y(\tau)$/HM at JPL	$5\times10^{-12}\tau^{-1/2}$	$10^{-11}\tau^{-1/2}$	
$\sigma_y(\tau)$ at JPL	$1.5\times10^{-11}\tau^{-1/2}$	$3\times10^{-11}\tau^{-1/2}$	
σ_y floor at JPL	2×10^{-14}	3×10^{-14}	
Drift (day)	-3.4×10^{-14}	9.3×10^{-15}	-1.6×10^{-14}
Retrace (±)	-6.3×10^{-12}	-2.5×10^{-12}	4.4×10^{-13}

Thai M. Hoang, et al., *Sci Rep* 13, 10629 (2023).
https://doi.org/10.1038/s41598-023-36411-x.

Independently Evaluated at US NRL



Shipping were done by commercial carriers and the clock packages arrived in working order.

Prototype	U3.2	U3.4	U3.5
Size	1.1 L	1.1 L	1.1 L†
Weight	1.2 kg	1.2 kg	1.2 kg†
Power	4.6 W	4.6 W	5.9 W
$\sigma_y(\tau)$/HM at JPL	$5 \times 10^{-12}\tau^{-1/2}$	$10^{-11}\tau^{-1/2}$	
$\sigma_y(\tau)$ at JPL	$1.5 \times 10^{-11}\tau^{-1/2}$	$3 \times 10^{-11}\tau^{-1/2}$	
σ_y floor at JPL	2×10^{-14}	3×10^{-14}	
$\sigma_y(\tau)$ at NRL	$2 \times 10^{-11}\tau^{-1/2}$	$3 \times 10^{-11}\tau^{-1/2}$	$10^{-11}\tau^{-1/2}$
σ_y floor at NRL	3×10^{-14}	$< 2 \times 10^{-13}$	2×10^{-14}
Drift (day)	-3.4×10^{-14}	9.3×10^{-15}	-1.6×10^{-14}
Retrace (±)	-6.3×10^{-12}	-2.5×10^{-12}	4.4×10^{-13}

Thai M. Hoang, et al., *Sci Rep* 13, 10629 (2023). https://doi.org/10.1038/s41598-023-36411-x.

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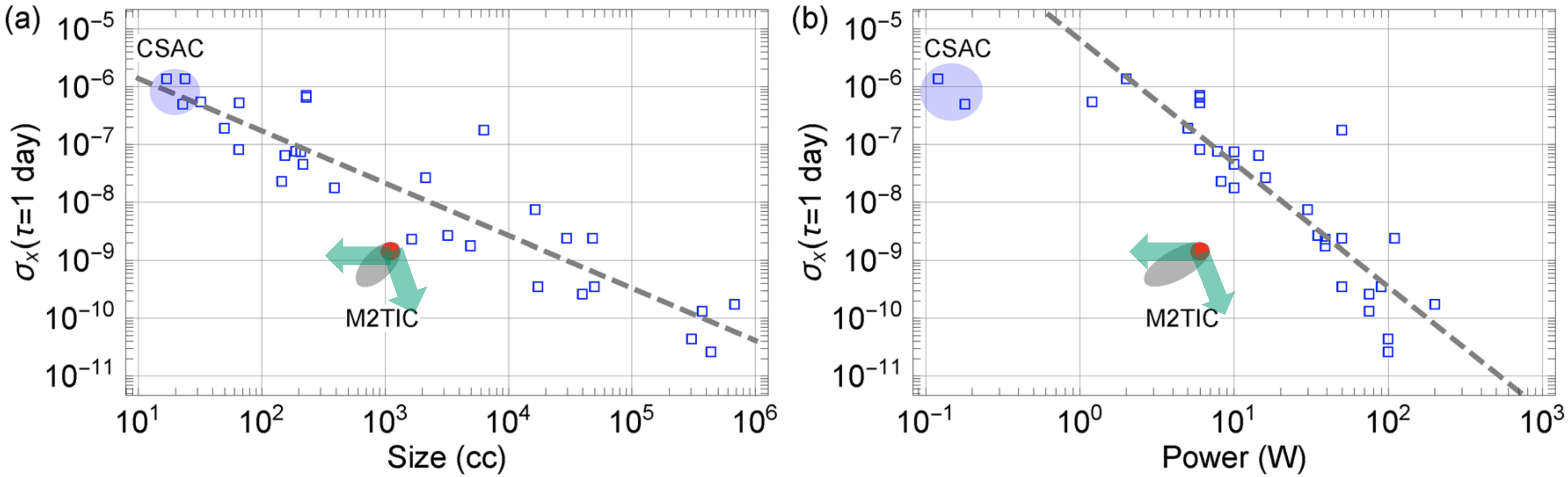
Summary and Outlook



Summary: we have been able to demonstrate M2TIC capable of providing the performance of the rack-mount 5071A Cs beam tube clocks in a much lower SWaP package.

What's next?

1. *SWaP* – There are paths to further SWaP reduction without loss of performances with adoption and use of new component technologies available.
2. *Performance* – The dominating instability sources are mainly from Second-order Zeeman shifts from various magnetic field sources and the second-order Doppler shifts from ion number variations. Both can be improved significantly within the current design architecture.

Acknowledgement

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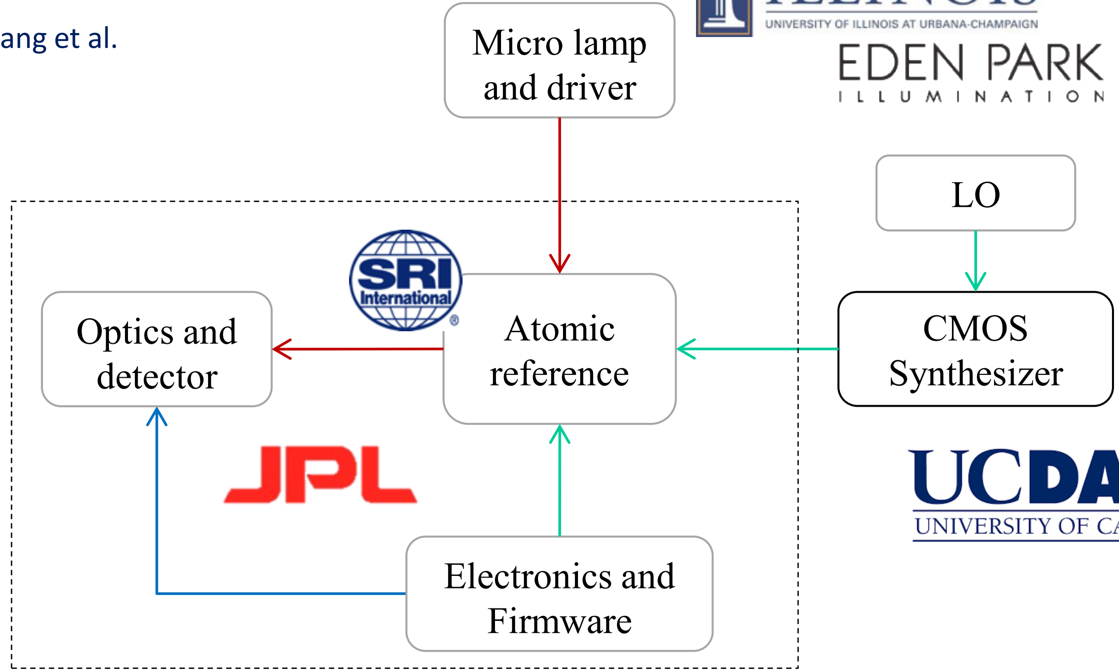

Micro lamp and driver

LO

CMOS Synthesizer

Atomic reference

Optics and detector

Electronics and Firmware

Quantum Sciences and Technology Group

Nan Yu (818)-354-4093 nan.yu@jpl.nasa.gov; http://quantum.jpl.nasa.gov

Study quantum systems and exploit quantum properties, and devel advanced clocks, sensors and precision measurement tools, and science exploration and fundamental physics measurements

Actively looking for new postdoc and staff members

Frequency Standards and Clocks

- *Small and micro atomic clock*
- *Trapped ion optical clocks*
- *Neutral lattice clocks*

Atomic Quantum Sensors

- *Quantum gravity gradiometer*
- *Atomic quantum accelerometers*
- *Atomic quantum magnetometer*
- *Quantum enhanced sensors*

Science and Experiments in Space

- *Fundamental Physics*
- *Ultra-cold atoms in space*
- *Planetary and Earth Sciences*
- *Space Comm and Navigation*

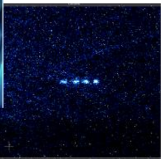
Light and Microwave Photonics

- *Micro resonator research and devices*
- *Nonlinear and quantum optics*
- *Frequency comb and applications*
- *Optical links at quantum limit*

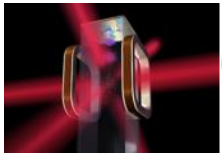
Trapped Hg ion Space clock (DSAC genesis)

Micro Mercury Trapped Ion Clock

Sr lattice clock

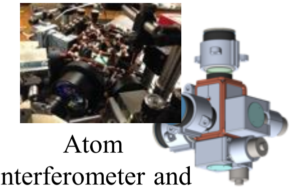


Miniature singly trapped Yb$^+$ optical clock

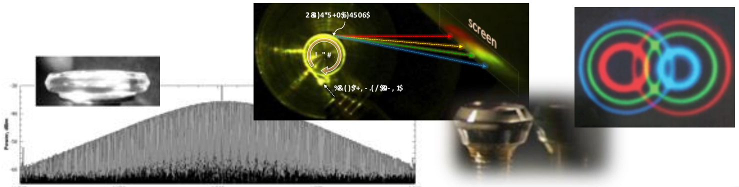


Cold Atom Laboratory

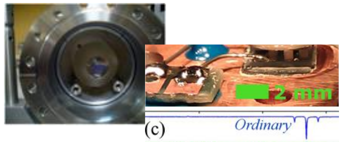
BEC-CAL



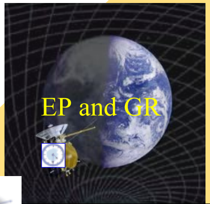
Atom interferometer and quantum sensors



Whispering Gallery mode resonators and quantum optics



Laser frequency and phase controls



Gravity, fundamental physics, and space science through precision measurements in space

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