Quantum Technologies for Atomic Clocks

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National Research Council Canada

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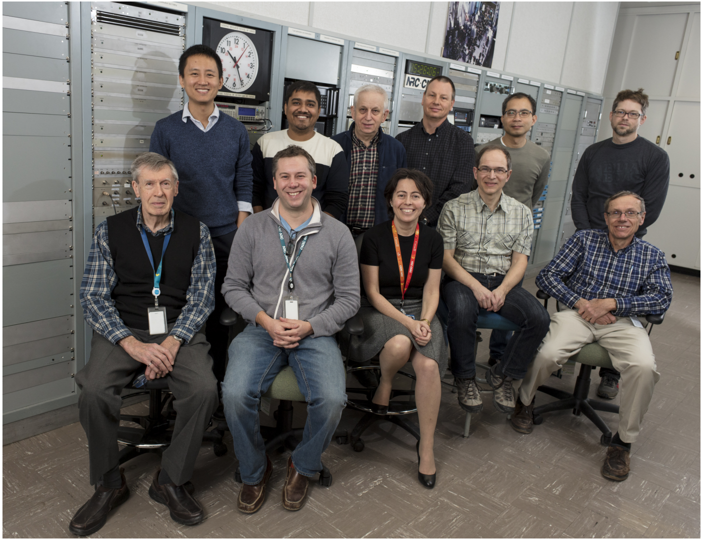
Frequency and Time Group



Front row:

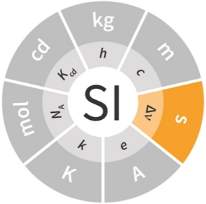
- John Alcock
- Scott Beattie
- Marina Gertsvolf
- Pierre Dubé
- John Bernard

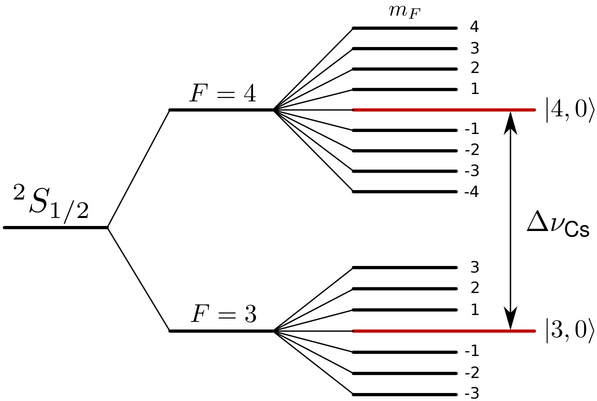
Back row:

- Bin Jian
- Deval Patel
- Wojciech Pakulski
- Bill Hoger
- Hai Pham
- André Charbonneau

Definition of the SI second

The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\mathrm{Cs}}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.



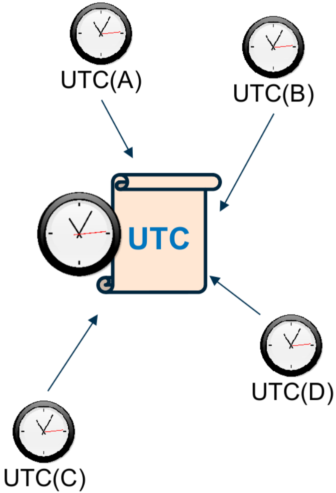


Quantum oscillator

The UTC timescale

Coordinated Universal Time (UTC) is the world's best approximation of the SI units for time and frequency.

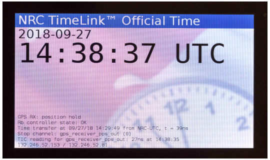
- Based on International Atomic Time (TAI):
  - *Combined output of about 400 atomic clocks from more than 50 national laboratories worldwide*
  - *UTC lags TAI by 37 (leap) seconds*
- Computed by the BIPM
- Published monthly in the Circular T



Frequency and Time activities at NRC

Time keeping and dissemination

- *Realization of the SI second with Cs clocks*
- *Keep official time for Canada*
- *Disseminate time to the public*
- *Contribution to international time: UTC(NRC)*



NRC TimeLink™ Official Time
2018-09-27
14:38:37 UTC

```
GPS RX: position hold
Rb controller state: OK
Time transfer at 09/27/18 14:29:49 from NRC-UTC, t - 39ns
Stop channel: gps_receiver_pps_out (0)
TIC reading for gps_receiver_pps_out: 27ns at 14:38:35
132.246.52.153 / 132.246.52.81
```

Calibration facilities

Calibration of clocks	*From chronometers to atomic clocks*
HeNe/I$_2$ *– 633 nm*	*633 nm lasers*
Femto combs	*Various stabilized lasers*
Acetylene stabilized lasers	*Telecom wavelengths references*

Research and development

Cs fountain clock	2.3×10^{-16}
Femto-combs	*Microwave to optical link*
^{88}*Sr*$^{+}$ *ion optical clock*	1×10^{-17}

Time keeping at NRC

- Ensemble of 6 commercial Cs clocks
- 2 masers
- 5 Global Nav. Satellite System receivers (GNSS)
- Cesium fountain clock (new)

Agilent 5071A Cs clock

Symmetricom hydrogen maser

Time dissemination

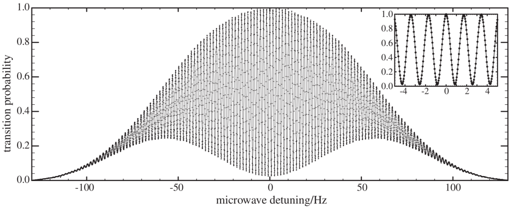
- NRC Timelink™ Services
  - *Remote clock (new)*
  - *Monitored NTP*
- Time signal on CBC radio / Radio-Canada
  - *Long dash, 80 years old.*
- Telephone talking clock
  - *613-745-1576*

Remote clock

Clock comparison and
time dissemination equipment

Cesium fountain clock – *NRC FCs2*

- Evaluation recently completed
- Accuracy $\sim 2.3 \times 10^{-16}$
- Stability $\sim 2 \times 10^{-13}$ at 1 s

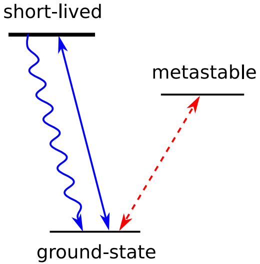


Ramsey fringes

Optical atomic clocks

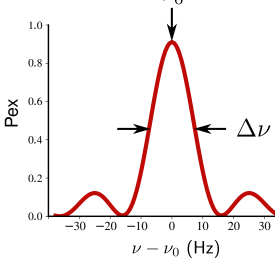
Nature-provided frequencies:

- Quantum reference
- Frequencies determined by physical constants
    - *not artifacts*
    - *reproducible, universal references*



Suitable transitions for accuracy and stability:

- High-frequency (optical): $\nu_0 \sim 10^{15}$ Hz
- Narrow linewidth: $\Delta\nu \lesssim 1$ Hz
- $Q \gtrsim 10^{15}$
- Small sensitivity to external perturbations

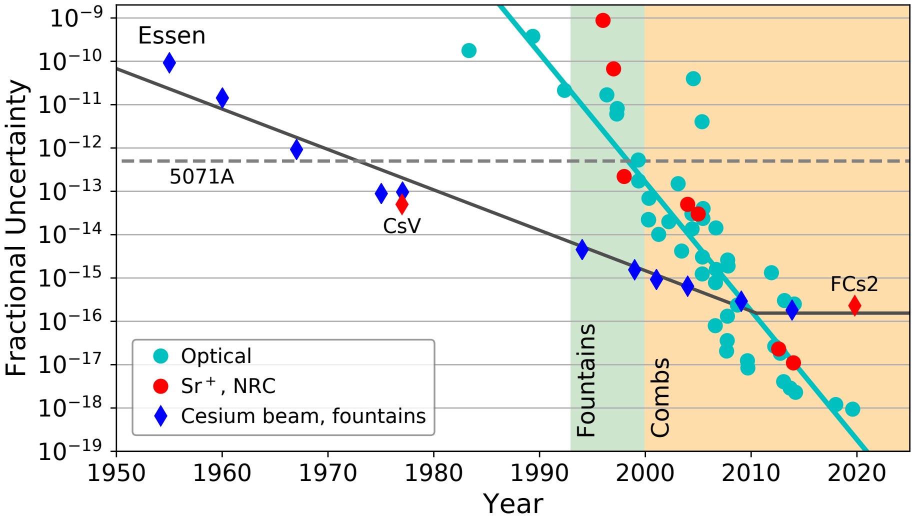


$$Q = \frac{\nu_0}{\Delta\nu}$$

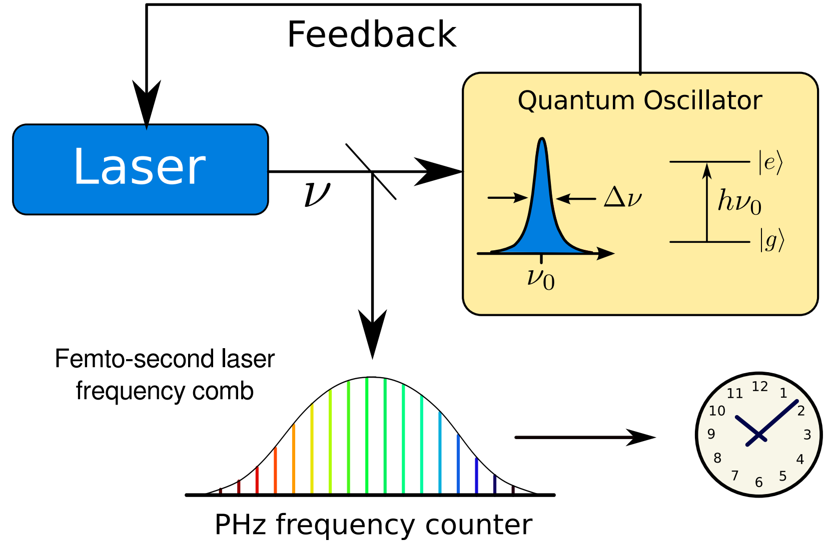
Some atomic systems investigated

Optical Ion Clocks	Optical Lattice Clocks
$^{27}\mathrm{Al}^{+}$	$^{24}\mathrm{Mg}$
$^{40}\mathrm{Ca}^{+}$	$^{87}\mathrm{Sr}$
$^{88}\mathrm{Sr}^{+}$	$^{171}\mathrm{Yb}$
$^{115}\mathrm{In}^{+}$	$^{199}\mathrm{Hg}$
$^{171}\mathrm{Yb}^{+}$	
$^{176}\mathrm{Lu}^{+}$	
$^{199}\mathrm{Hg}^{+}$	

Atomic clocks uncertainties

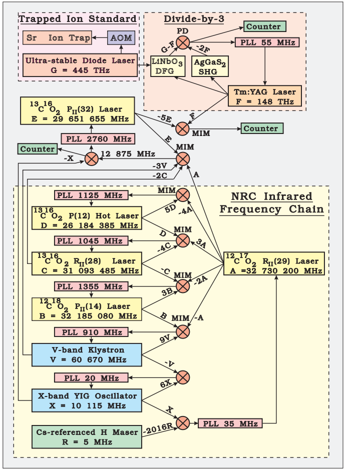


Optical clock components



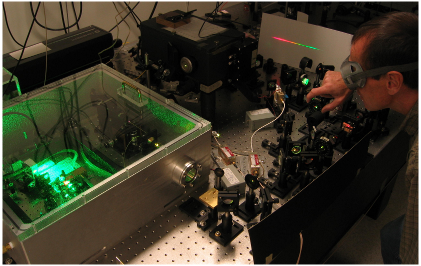
Counting optical frequencies

Before 2000

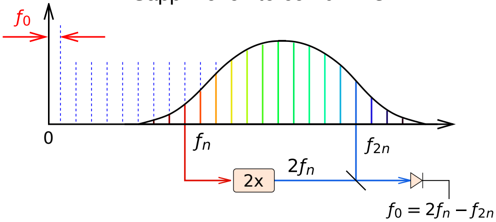


Frequency synthesis chain

Since 2000



Ti:Sapphire femto-comb NRC

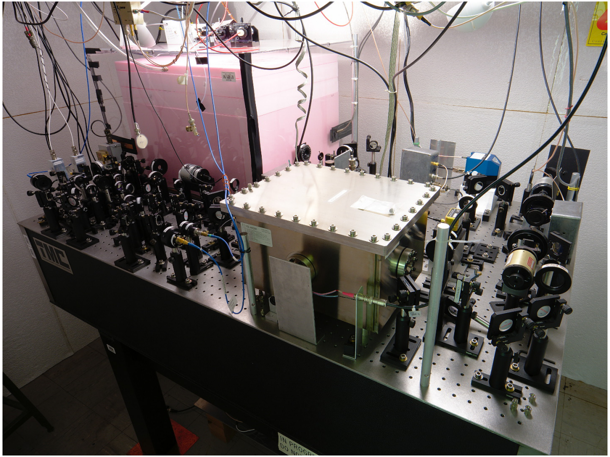


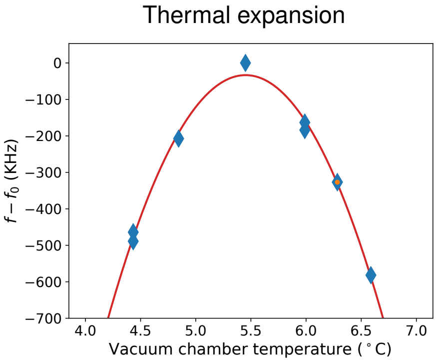
2005 Nobel Laureates

Jan Hall

Ted Hänsch

NRC clock laser for $^{88}\mathrm{Sr}^+$

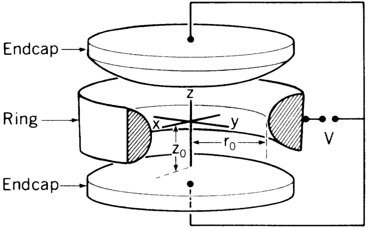


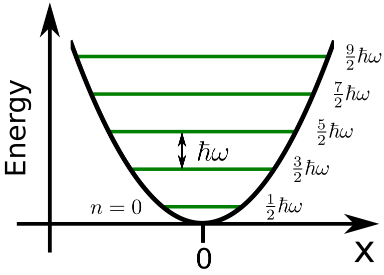

Thermal expansion

Cavity properties:

- $T_0 = 5.45(1)^\circ$C
- $\alpha \lesssim 2 \times 10^{-11}/^\circ$C
- Isothermal creep $= 2 \times 10^{-17}/s$

Ion trapping



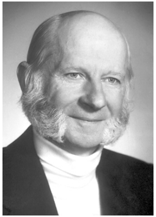


Secular frequency:
$\omega/2\pi \sim$ MHz

Benefits:

- Unlimited interaction times
- No Doppler broadening
- Well-controlled environment
- $< 10^{-18}$ uncertainty demonstrated

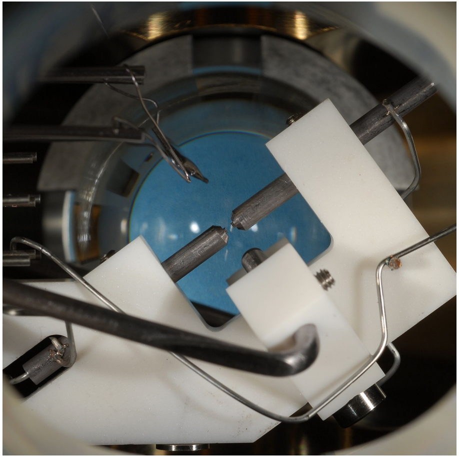
1989 Nobel Laureates



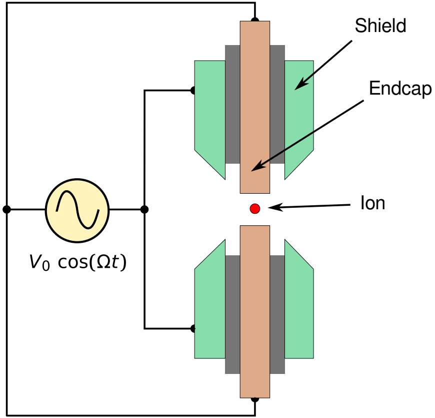
Hans Dehmelt

Wolfgang Paul

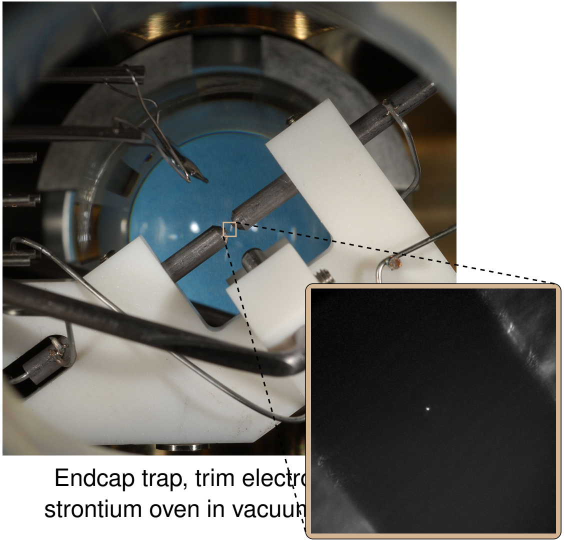
$^{88}\mathrm{Sr}^{+}$ ion trap at NRC



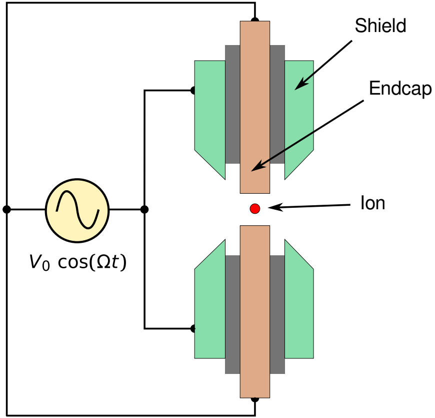
Endcap trap, trim electrodes, and strontium oven in vacuum chamber



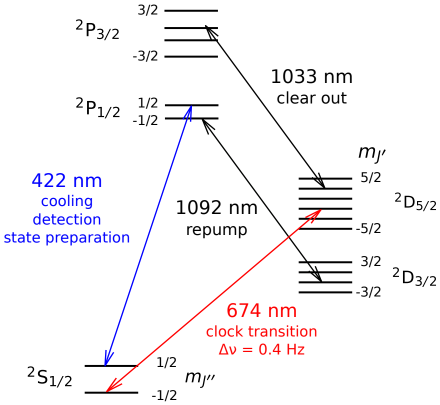
^{88}Sr^{+} ion trap at NRC

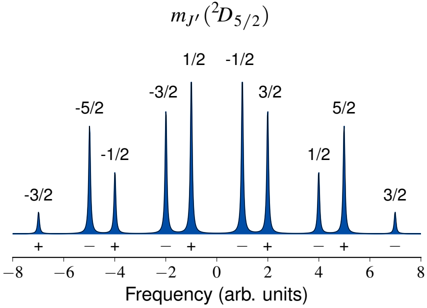


Endcap trap, trim electr
strontium oven in vacuu



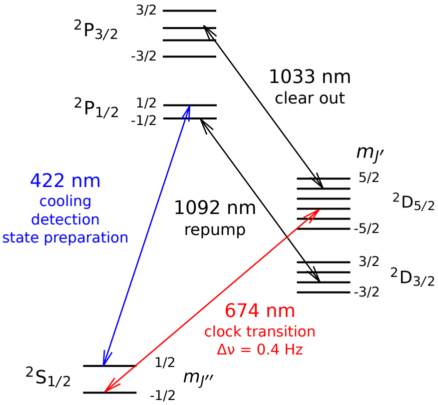
^{88}Sr^{+} optical clock



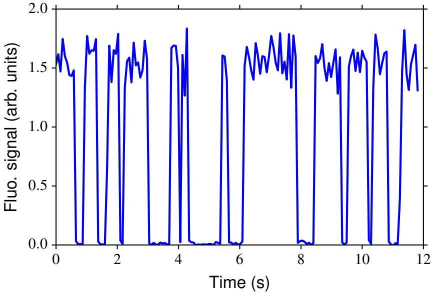


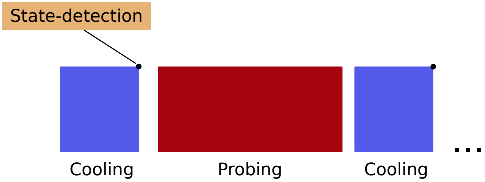
S–*D* Zeeman Spectrum

$^{88}Sr^{+}$ optical clock

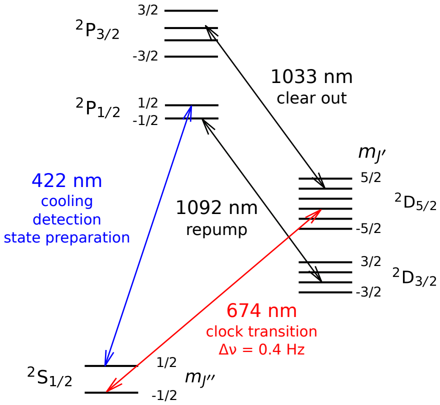


Quantum Jump Signal



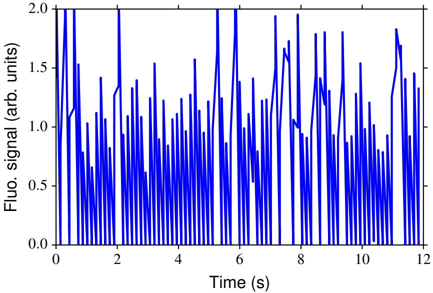


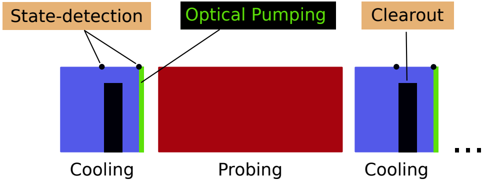
^{88}Sr^{+} optical clock



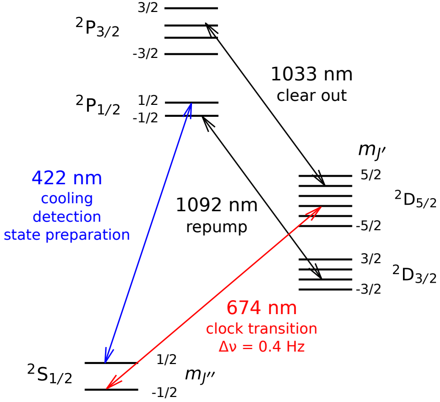
P. Dubé *et al.*, Phys. Rev. A **92**, 042119 (2015).

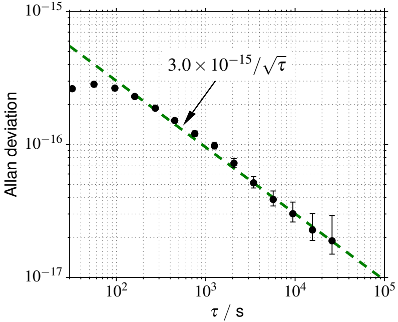
State-prepared → higher S/N





$^{88}\mathrm{Sr}^{+}$ optical clock





Stability observed with state preparation

P. Dubé *et al.*, Phys. Rev. A **92**, 042119 (2015).

Fundamental shifts in single-ion clocks

Shift	Causes
Stark	micromotion, secular motion blackbody radiation laser light
2^{nd}-order Doppler	micromotion, secular motion
Electric quadrupole	$\nabla \vec{E}$
Quadratic Zeeman[a]	$\langle B^2 \rangle$
Collisions	background gas

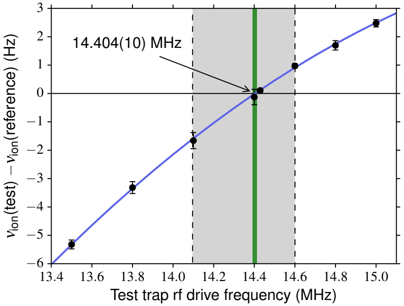
[a] For $B = 3.892(3)\ \mu$T: QZS $= 1.063(2) \times 10^{-19}$

Special frequency shift control methods in ^{88}Sr^{+}

- Zeeman averaging of $^{2}D_{5/2}$ sublevels [†]
  - *Electric quadrupole shift* $\approx 10^{-20}$
  - *Tensor Stark shifts* $\approx 10^{-21}$

- Operation at magic rf trap frequency [⋆]

  At $\Omega_0/2\pi = 14.404$ MHz, TD $+$ Stark $\simeq 0$
  - *μ-motion shifts reduced by* $> 400\times$ $\approx 10^{-19}$
  - *Thermal motion shifts reduced by* $\sim 3\times$ $\approx 10^{-18}$



Independent of design

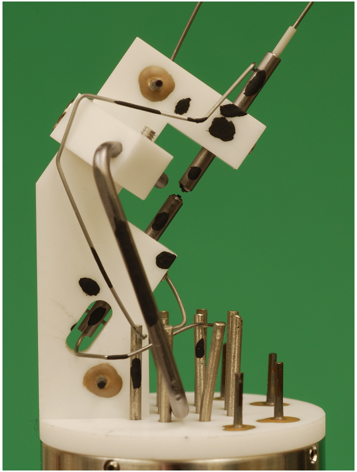
[†] P. Dubé *et al.*, Phys. Rev. Lett. **95**, 033001 (2005).
[†] P. Dubé *et al.*, Phys. Rev. A **87**, 023806 (2013).
[⋆] P. Dubé *et al.*, Phys. Rev. Lett. **112**, 173002 (2014).

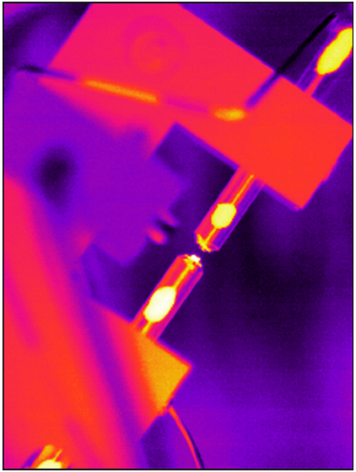
^{88}Sr^{+} simplified uncertainty budget

Source of shift	Current trap
BBR field evaluation, $\langle E^2 \rangle_T$	**11**
Thermal motion (D2+Stark)	1
BBRS coefficient, $\Delta\alpha_0$	0.83
Collisional shift [a]	0.6
1092 nm ac Stark shift	0.1
Excess micromotion	0.1
Electric quadrupole shift	0.03
Total	11×10^{-18}

[a] A.C. Vutha *et al.*, Phys. Rev. A **96**, 022704 (2017).

Thermal imaging of dummy ion trap





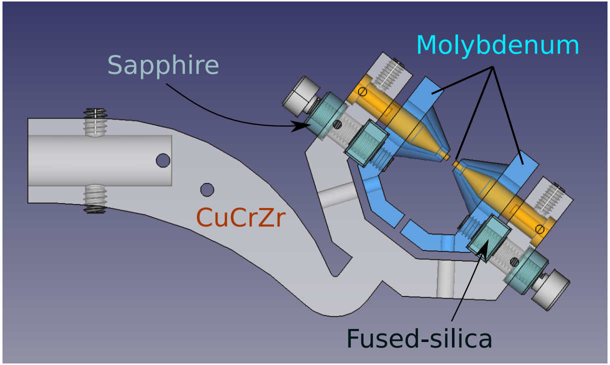
rf drive: 424 V_{pp}, 14.4 MHz

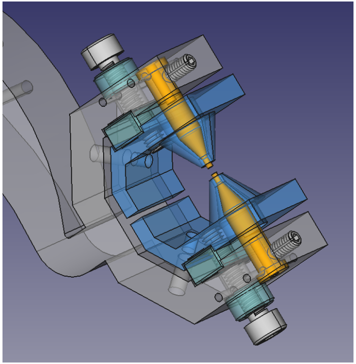
BBR shift is the main source of uncertainty

Possible solutions:

- Measurements + thermal modeling to determine $\langle E^2 \rangle_T$
- Improved trap design

Ion trap design for a transportable optical clock





- Mount material: copper alloy
- Electrodes: molybdenum
- Spacers: fused silica and sapphire

- Endcaps spacing: 0.84 mm
- $\angle(\vec{z}_{lab}, \vec{z}_{trap}) = 54.7^\circ$

^{88}Sr^{+} projected uncertainty budget

Source of shift	Current trap	Future trap
BBR field evaluation, $\langle E^2\rangle_T$	**11**	**1** [a]
Thermal motion (D2+Stark)	1	0.8 [b]
BBRS coefficient, $\Delta\alpha_0$	0.83	0.83
Collisional shift [c]	0.6	0.6
1092 nm ac Stark shift	0.1	0.1
Excess micromotion	0.1	0.1
Electric quadrupole shift	0.03	0.03
Total	11×10^{-18}	1.7×10^{-18}

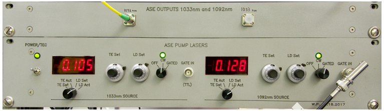
[a] P.B.R. Nisbet-Jones *et al.*, Appl. Phys. B **122**, 57 (2016).
$\Delta T_{BBR} = 0.14 \pm 0.14$ K

[b] ASE repump gives lower motional temperature than laser

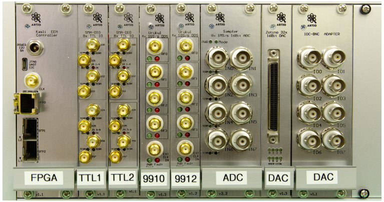
[c] A.C. Vutha *et al.*, Phys. Rev. A **96**, 022704 (2017).

Summary and outlook

- Methods are used to cancel or strongly reduce important systematic shifts of $^{88}\mathrm{Sr}^{+}$
- BBR field evaluation is the dominant uncertainty
- New ion trap designed for much lower BBR shift
  - *Expected uncertainty* $\sim 2 \times 10^{-18}$
- New technologies to reduce complexity and size
  - *ASE sources*[†]
  - *FPGA-based control system, etc...*
- Transportable system for frequency transfer between NRC and other NMI's at $\lesssim 10^{-17}$ level



1033 and 1092 nm ASE sources



FPGA-based data-acquisition and control

[†] T. Fordell *et al.*, Opt. Lett. **40**, 1822–1825 (2015).

Outlook II

SI second

- Re-definition with an optical transition

Fundamental tests with optical clocks

- General relativity
- Variations of fundmantal constants
- Local position invariance
- Lorentz symmmetry
- Dark matter detection, . . .

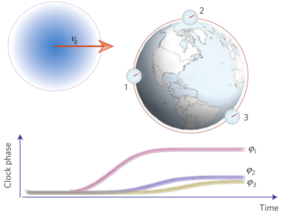
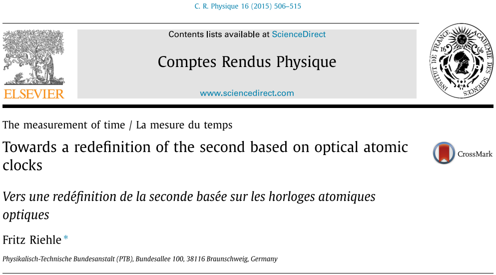


Figure 2 | **Effect of a monopole-type defect on atomic clocks.**



C. R. Physique 16 (2015) 506–515

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The measurement of time / La mesure du temps

Towards a redefinition of the second based on optical atomic clocks

Vers une redéfinition de la seconde basée sur les horloges atomiques optiques

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nature physics

LETTERS

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Hunting for topological dark matter with atomic clocks

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