SAND2021-11048PE

Sandia National Laboratories

Microwave Ion clock technologies

Office of Naval Research
Science & Technology

Dan Thrasher, PhD

Northrop Grumman Corp.

Woodland Hills CA

9/10/2021

U.S. DEPARTMENT OF ENERGY

NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

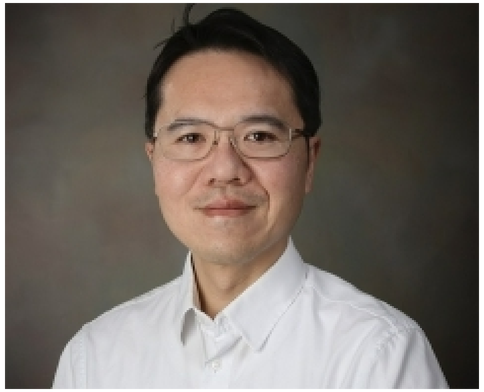
- My Biography
- Microwave Ion clock technologies (Sandia National Lab, ONR)
  - *Motivation*
  - *Physics*
  - *Setup*
  - *Results*
  - *Future*

Biography: Mentors

Scott Bergeson (BYU)
Ultra-cold neutral plasma

Andy Kung (Academia Sinica, TW)
Ultra-fast phenomena

Thad Walker (UW-Madison)
NMR gyroscope



Yuan-Yu Jau and **Peter Schwindt** (SNL)
Microwave ion clock

Biography: 2020-2021 grant applications

Vectorized **E**arth's-field **N**on-magnetic **O**ptical-pumped **M**agnetometer (VENOM), DARPA-SAVaNT

Quantum **O**ptimal **C**ontrol **C**omagnetometry (QOCC), DOE-Quantum Horizons *pending*

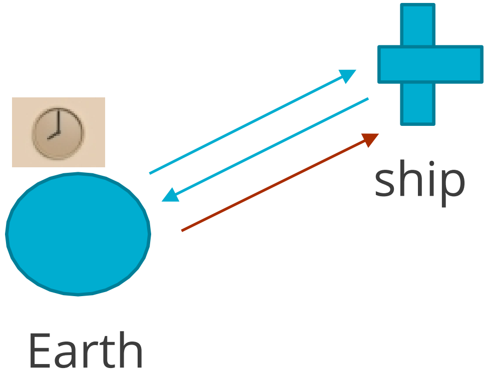
Remote **A**tomic **G**radiometric **E**avesdropping (RAGE), DII-NRO *pending*

Motivation

- What is the problem?
- What are the applications?
- What is the state of the art?
- Why Yb?
- Timeline and milestones?

Motivation: applications

Problem: Low SWaP and high stability *fieldable* clock



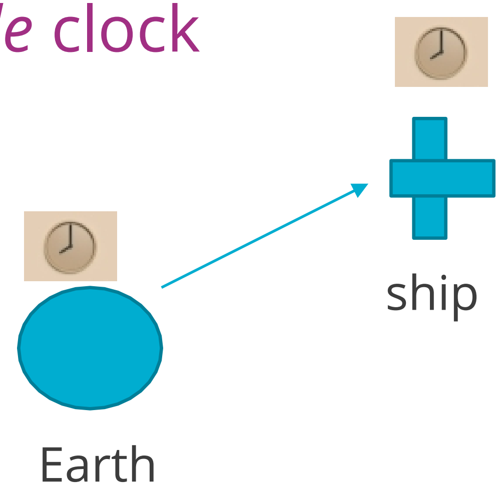
40 min to ascertain position near mars

Applications

- Deep space navigation
- Global navigation satellite systems
- Global positioning system denied navigation
- Fundamental physics

Motivation: applications

Problem: Low SWaP and high stability *fieldable* clock



Applications

- Deep space navigation
- Global navigation satellite systems
- Global positioning system denied navigation
- Fundamental physics

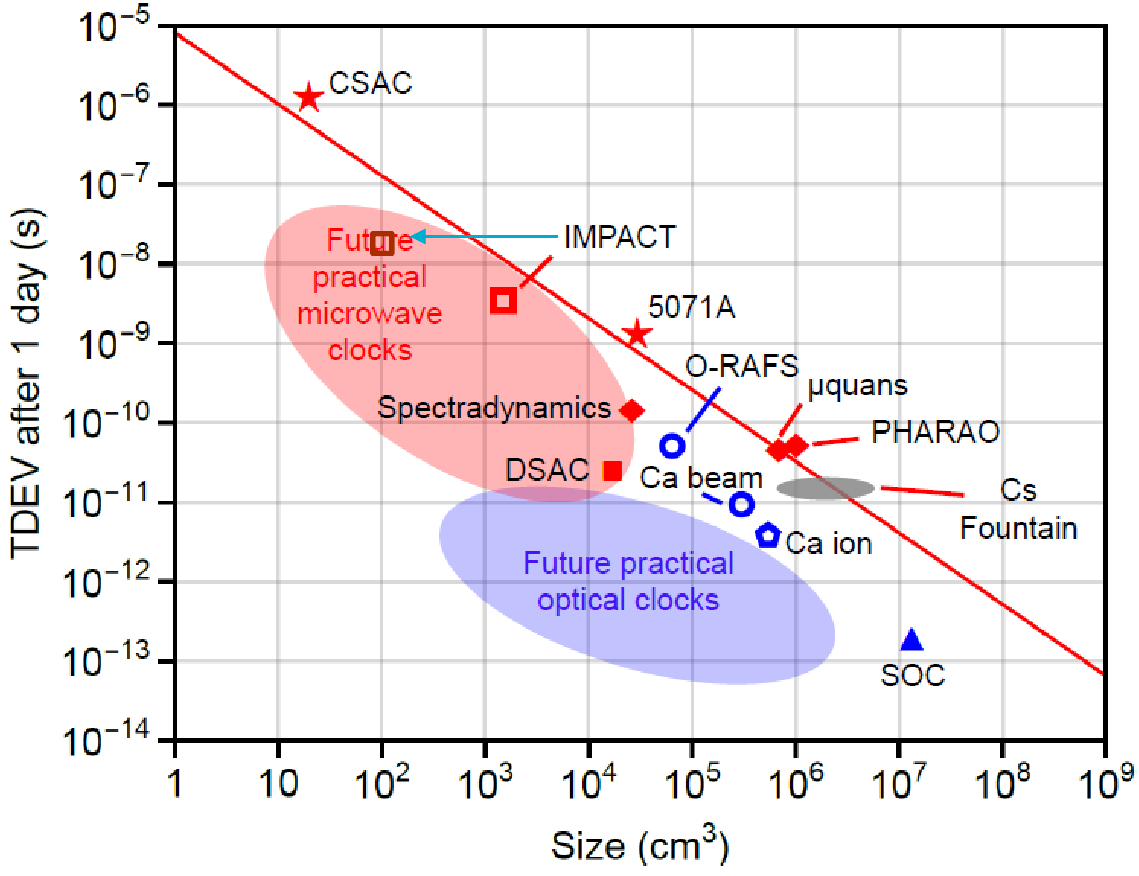

Article

Demonstration of a trapped-ion atomic clock in space

https://doi.org/10.1038/s41586-021-03571-7
Received: 4 December 2020
Accepted: 21 April 2021

E. A. Burt[1,2]✉, J. D. Prestage[1,2], R. L. Tjoelker[1,2], D. G. Enzer[1], D. Kuang[1], D. W. Murphy[1], D. E. Robison[1], J. M. Seubert[1], R. T. Wang[1] & T. A. Ely[1]

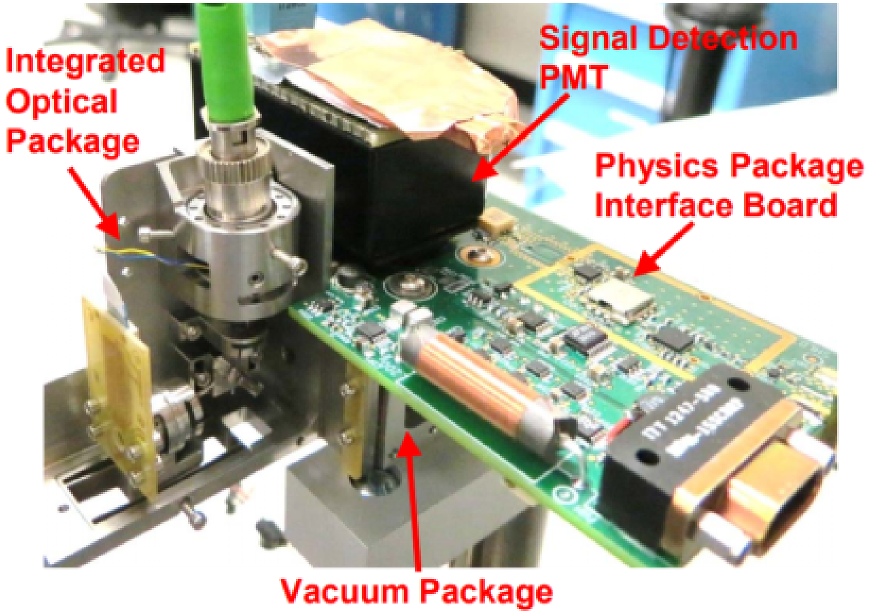
Motivation: state of the art

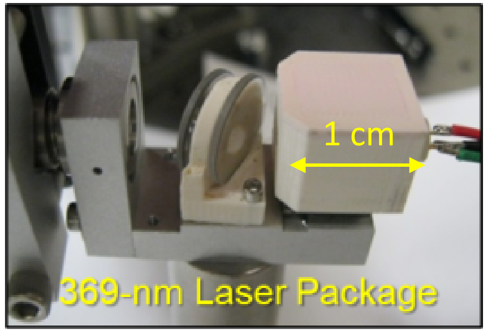


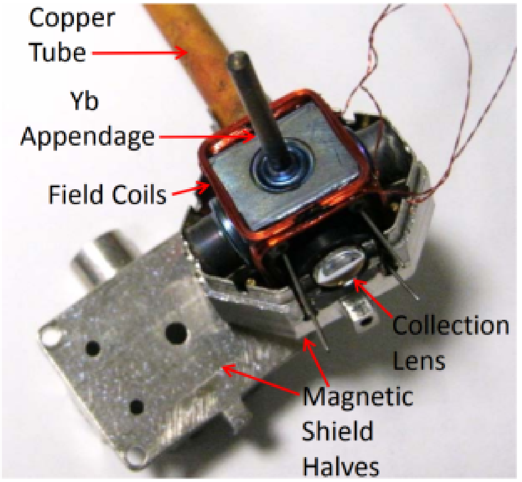
Microwave systems
- ★ Commercial clock
- ◆ Cold atom clock
- ◻ Ion physics package
- ■ Ion clock

Optical systems
- ○ Thermal atom physics package
- ⬠ Ion physics package
- ▲ Optical lattice clock

Schmittberger 2020 (arXiv:2004.09987v1)

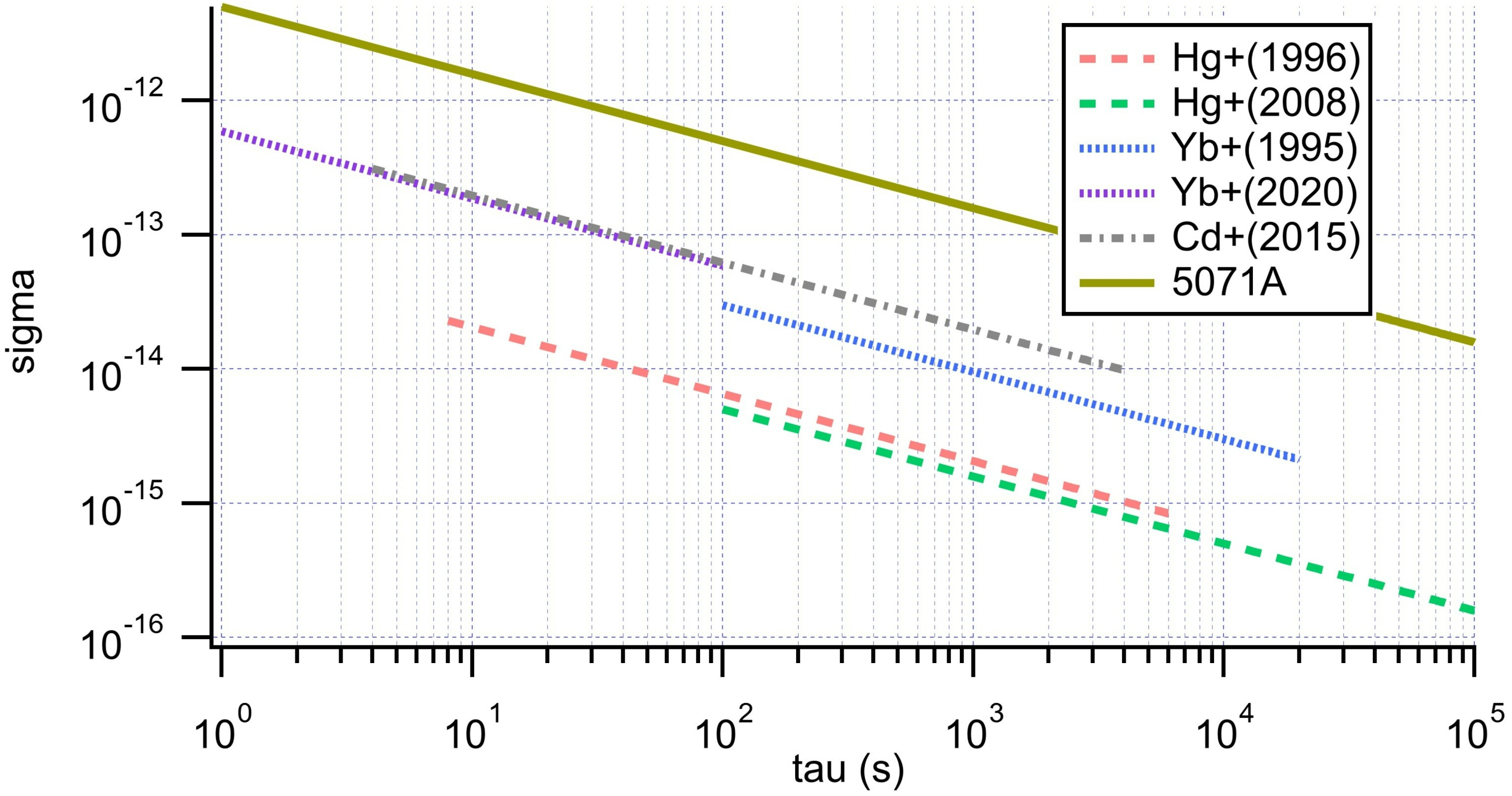






P. D. D. Schwindt *et al.*, "Miniature trapped-ion frequency standard with $^{171}Yb^{+}$", 2015

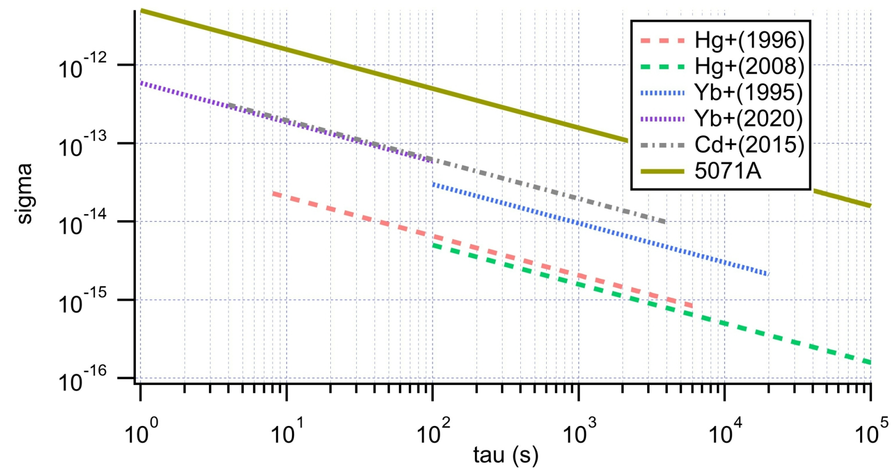
Motivation: state of the art



Motivation: state of the art

Ion species comparison

Ion	I	ν (GHz)	NLZ (Hz/G^2)	λ (nm)	Cycling?	Vapor Pressure	Toxic
199Hg	1/2	40 ✓	97 ✓	194 ✗	No ✗	High ✓	Yes ✗
171Yb	1/2	13 ✗	311 ✗	369 ✓	Yes ✓	low ✗	No ✓



Motivation: state of the art

Ion species comparison

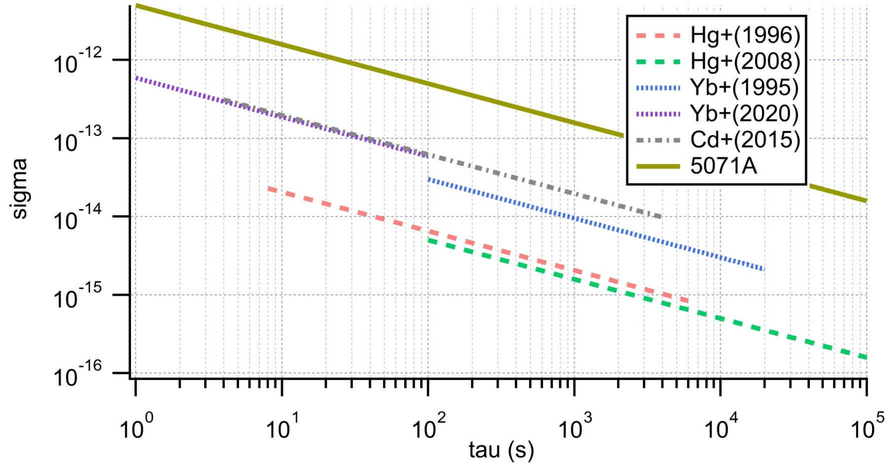
Ion	I	ν (GHz)	NLZ (Hz/G^2)	λ (nm)	Cycling?	Vapor Pressure	Toxic
199Hg	1/2	40 ✓	97 ✓	194 ✗	No ✗	High ✓	Yes ✗
171Yb	1/2	13 ✗	311 ✗	369 ✓	Yes ✓	low ✗	No ✓

- Fieldable laser at 197 nm not (yet?) feasible.

Use discharge lamp instead (very robust).

- High scattering rate of Yb and possibility of fieldable laser

At 369 nm very promising!



Motivation: state of the art

Office of Naval Research: POP 2020-2022

Goal: Demonstrate high stability Yb+ microwave clock with new DFB laser diode

Clock Development

- Short term stability: $\frac{\delta\nu}{\nu} < 5 \text{ x } 10^{-13}\tau^{-1/2}$
- Long term stability: $\frac{\delta\nu}{\nu} < 5 \text{ x } 10^{-15}$ $(10^5 < \tau < 10^6)$

369 nm laser Development

- Distributed feedback (DFB) single frequency at 369.5 nm
- Continuous wave operation
- Output power > 100 μW
- Sufficient stability to demonstrate ion clock interrogation over >100 hr.

Motivation: state of the art

Office of Naval Research: POP 2020-2022

Goal: Demonstrate high stability Yb+ microwave clock with new DFB laser diode

Clock Development

- Short term stability: $\frac{\delta\nu}{\nu} < 5 \times 10^{-13}\tau^{-1/2}$
- Long term stability: $\frac{\delta\nu}{\nu} < 5 \times 10^{-15}$ $(10^5 < \tau < 10^6)$

369 nm laser Development

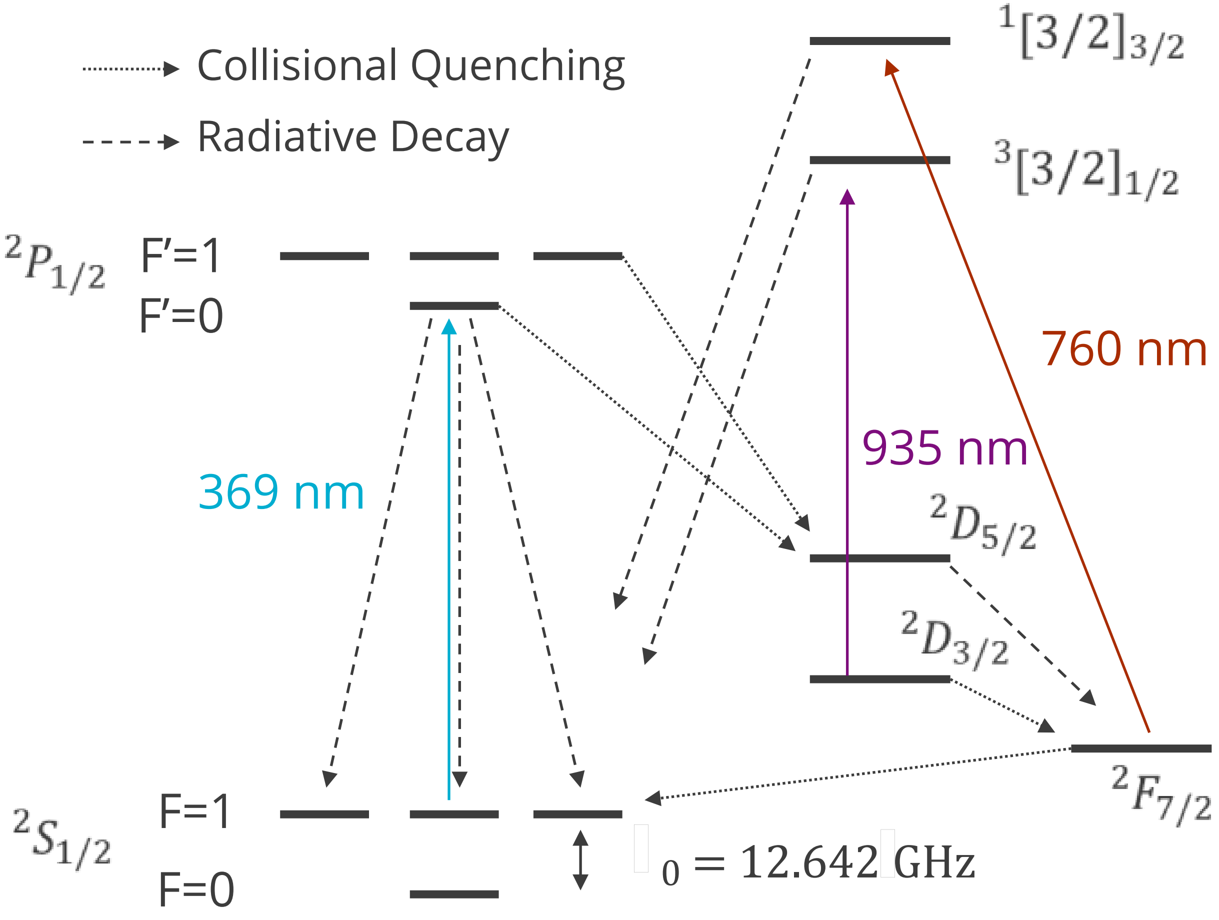
- Distributed feedback (DFB) single frequency at 369.5 nm
- Continuous wave operation
- Output power > 100 μW
- Sufficient stability to demonstrate ion clock interrogation over >100 hr.

Physics

- How does the clock operate?
- What determines the clock’s performance?

Physics: operation

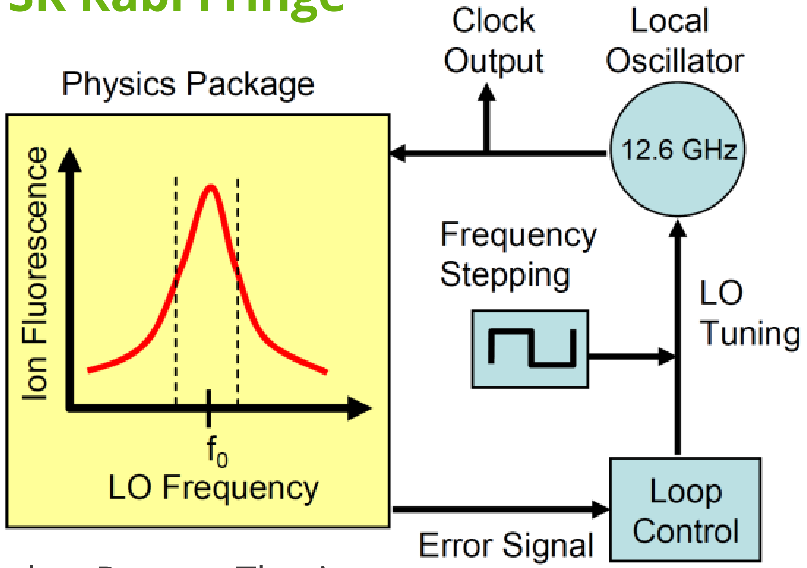
$^{171}Yb^+$ Energy level diagram



Adapted from AIP Advances 5, 117209 (2015)

Features:
- No first order Zeeman
- Buffer gas quenching and cooling
- Re-pump lasers: 935 and 760 nm

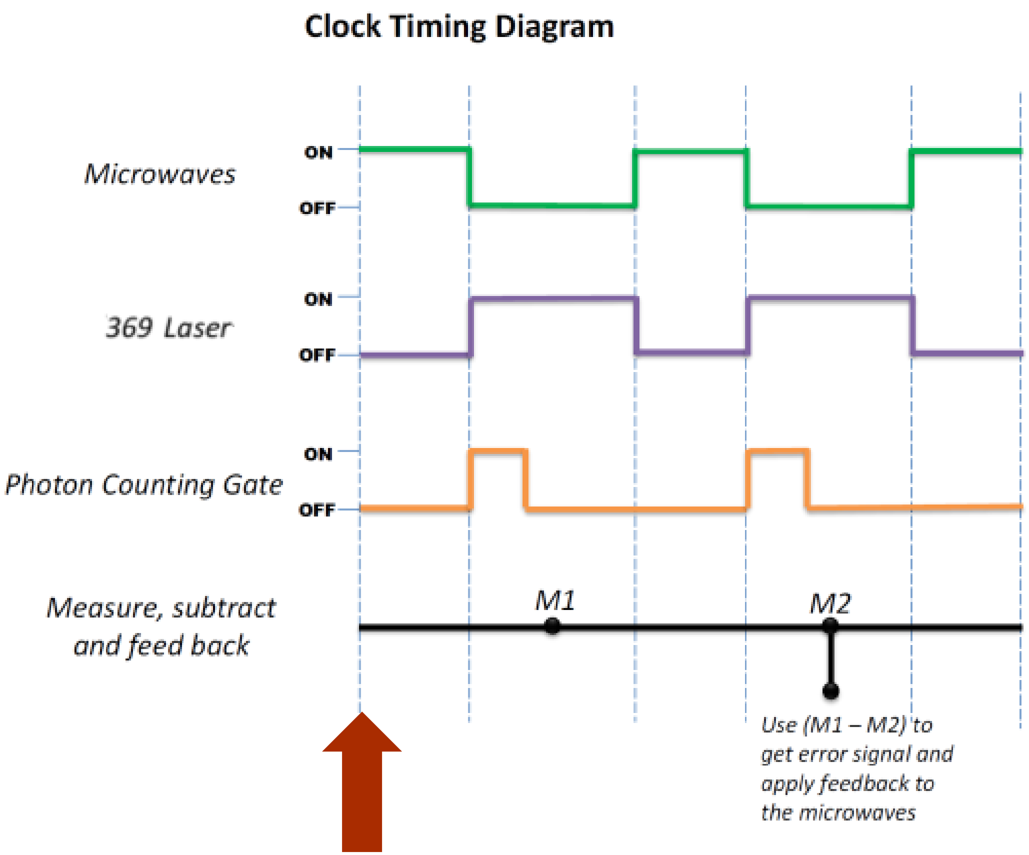
FSK Rabi Fringe



Heather Partner Thesis

Physics: operation

Clock Operation



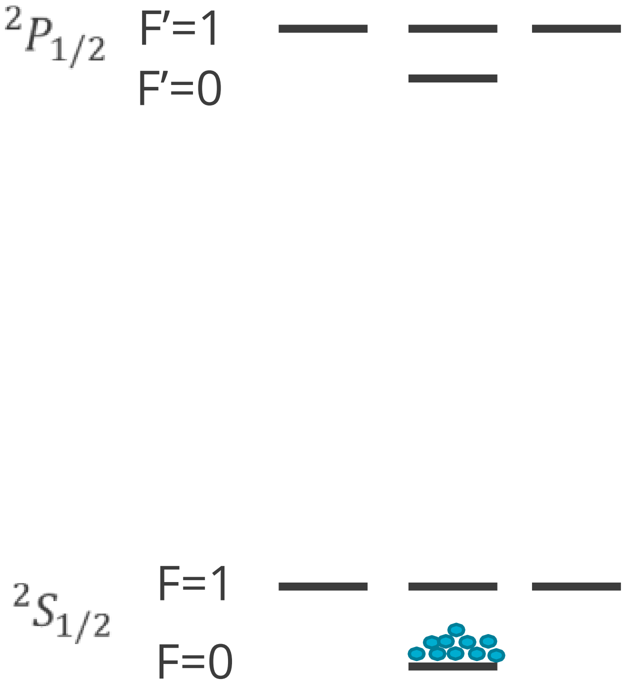
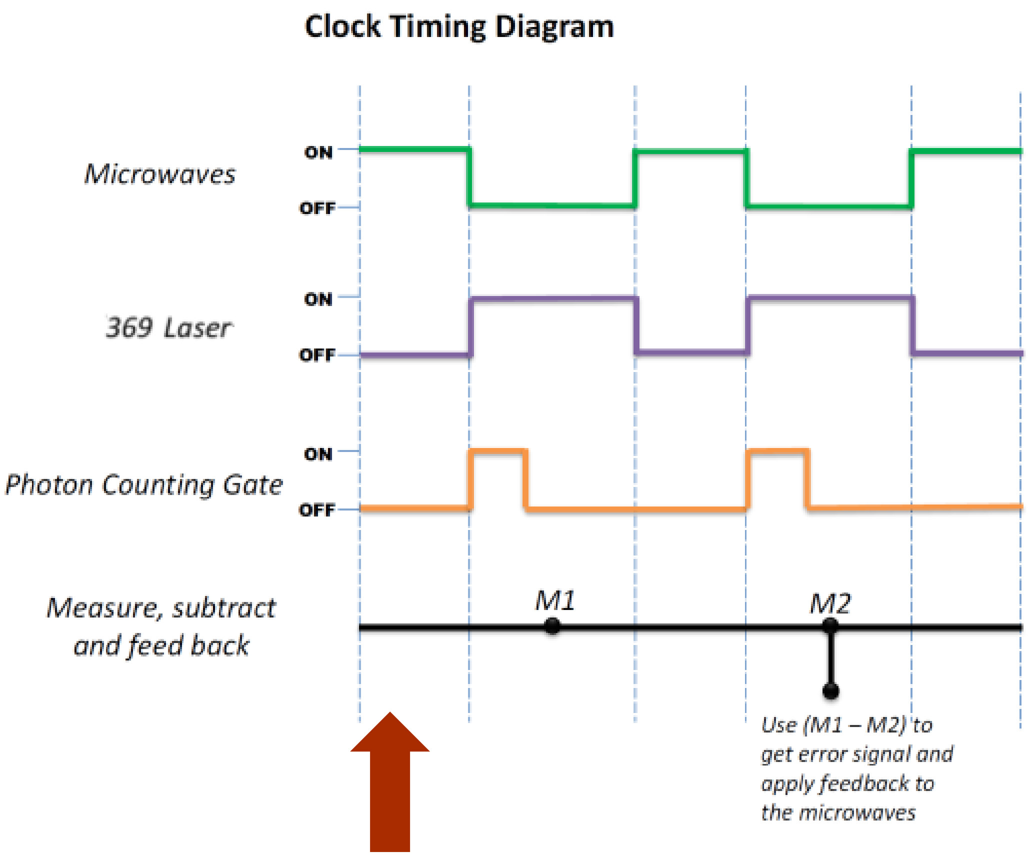


Image credit: Heather Partner Thesis

Physics: operation

Clock Operation



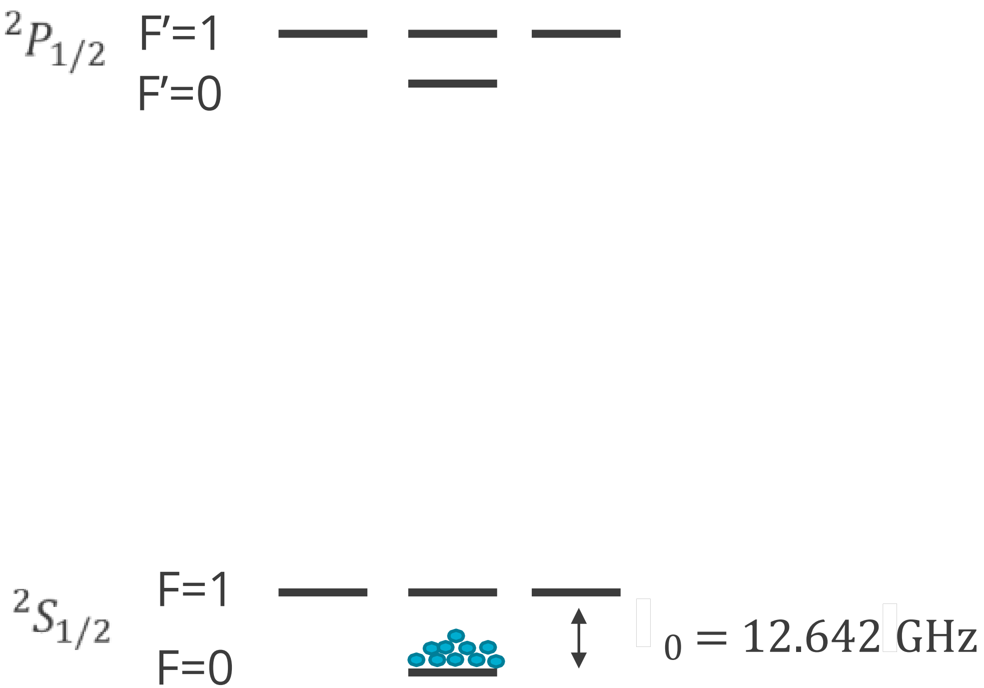
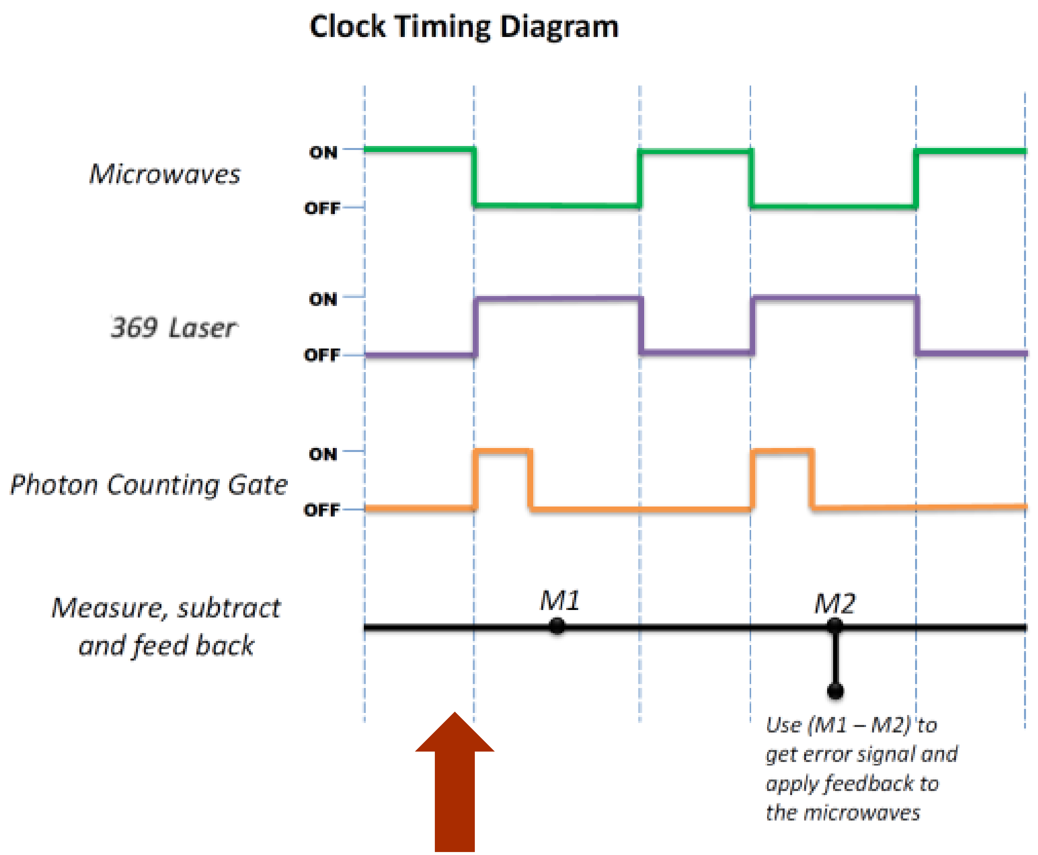


Image credit: Heather Partner Thesis

Physics: operation

Clock Operation



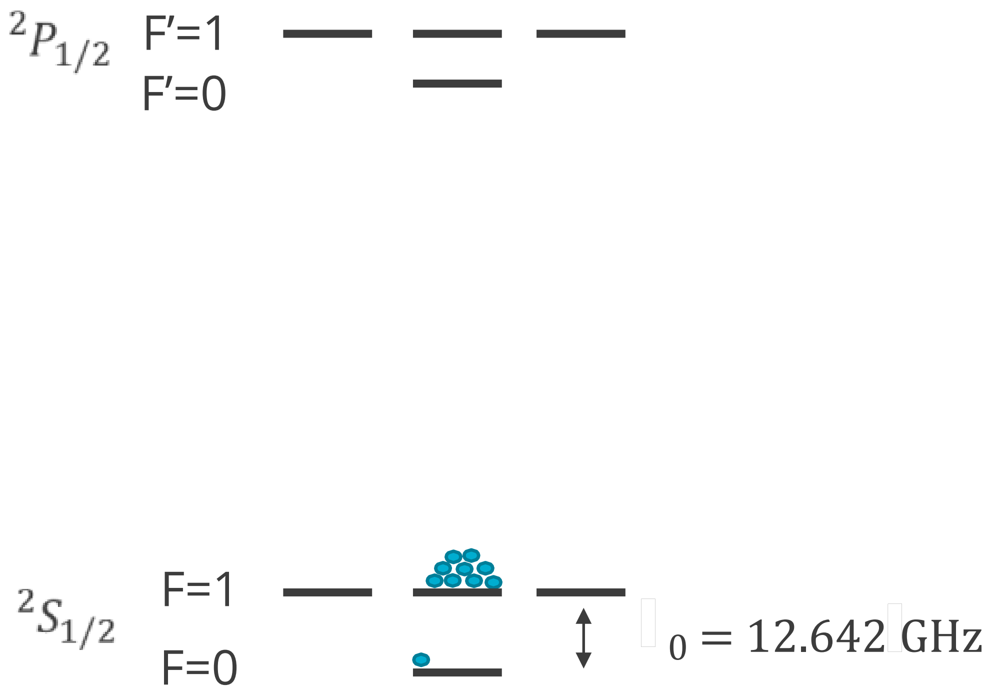
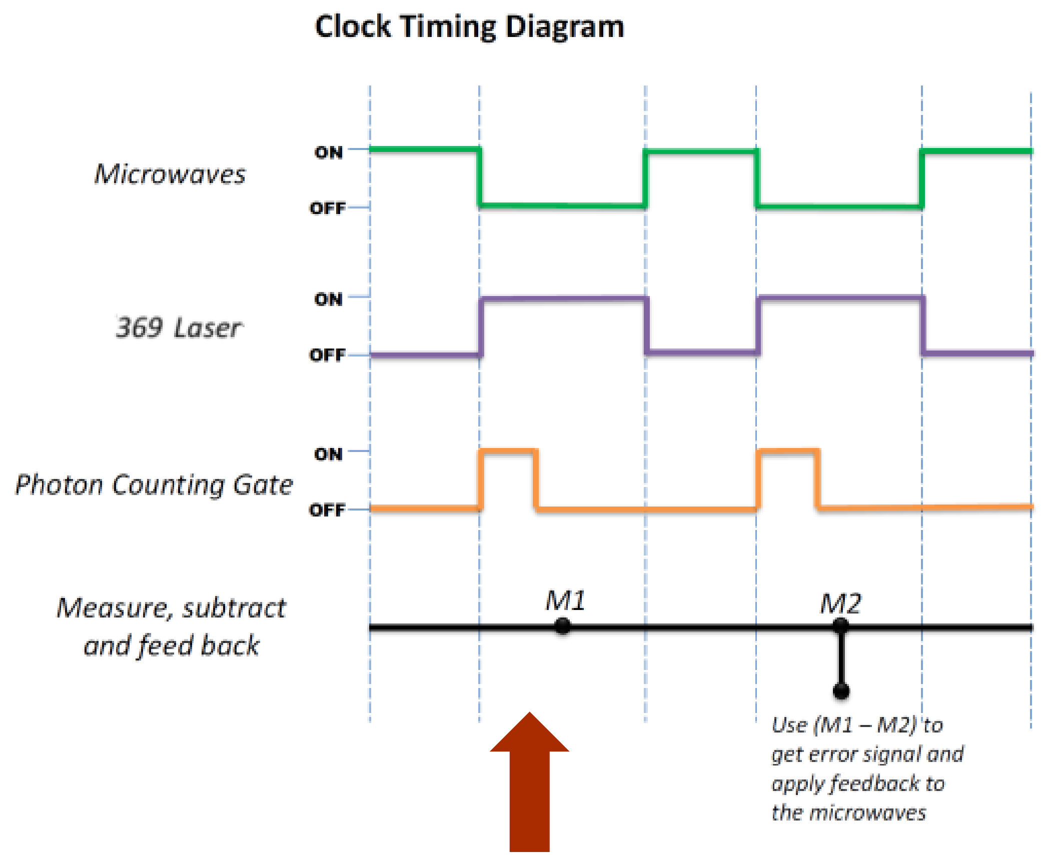


Image credit: Heather Partner Thesis

Physics: operation

Clock Operation



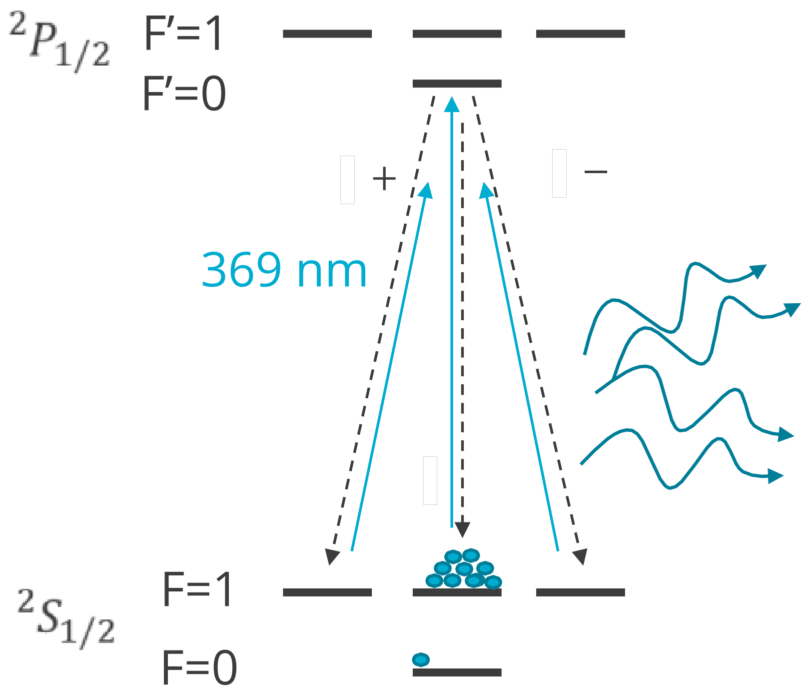
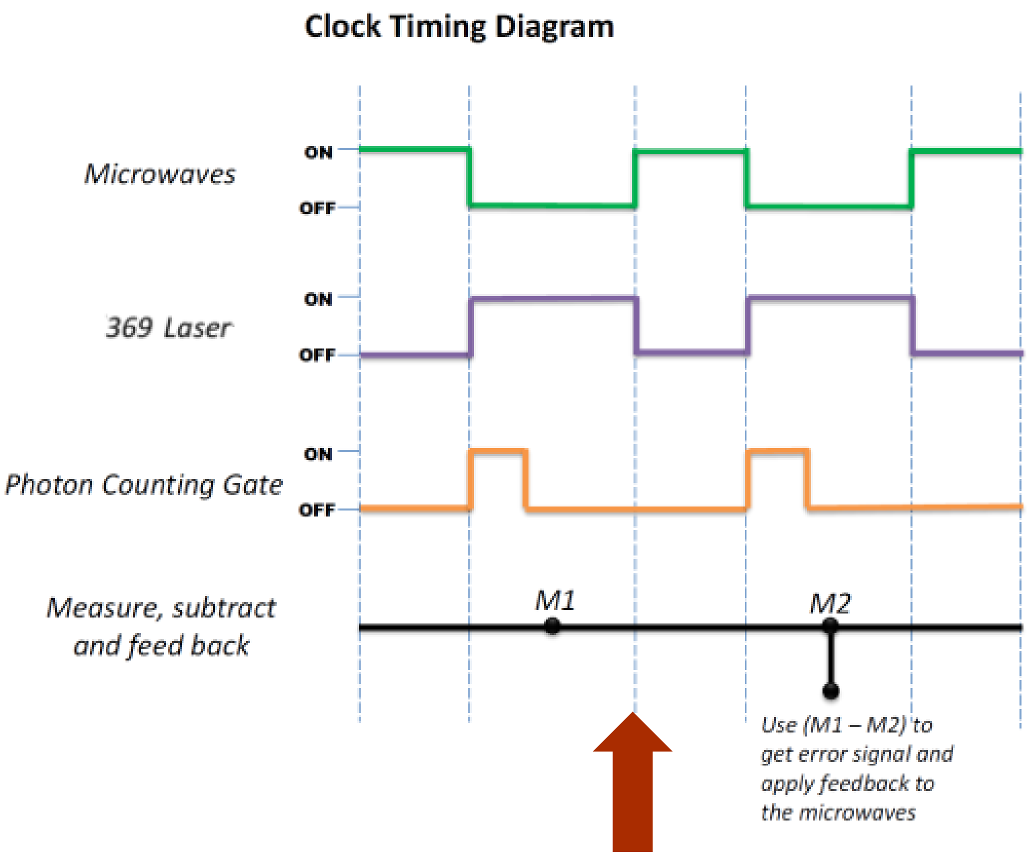


Image credit: Heather Partner Thesis

Physics: operation

Clock Operation



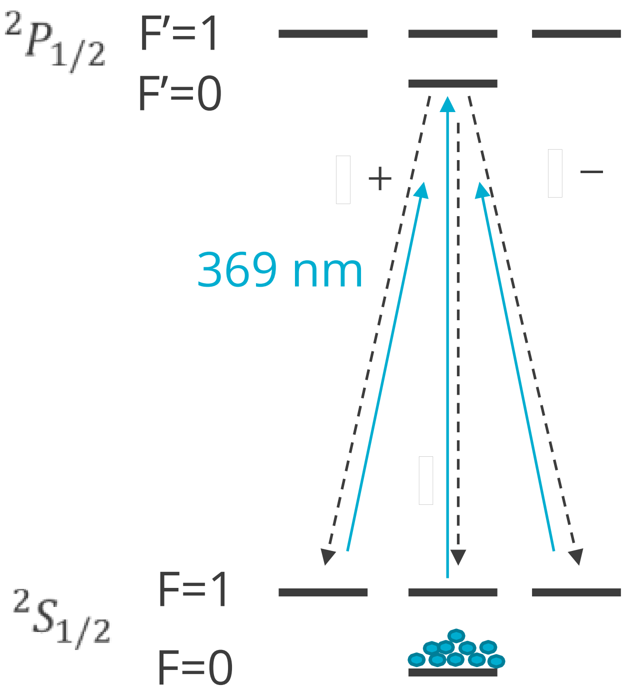


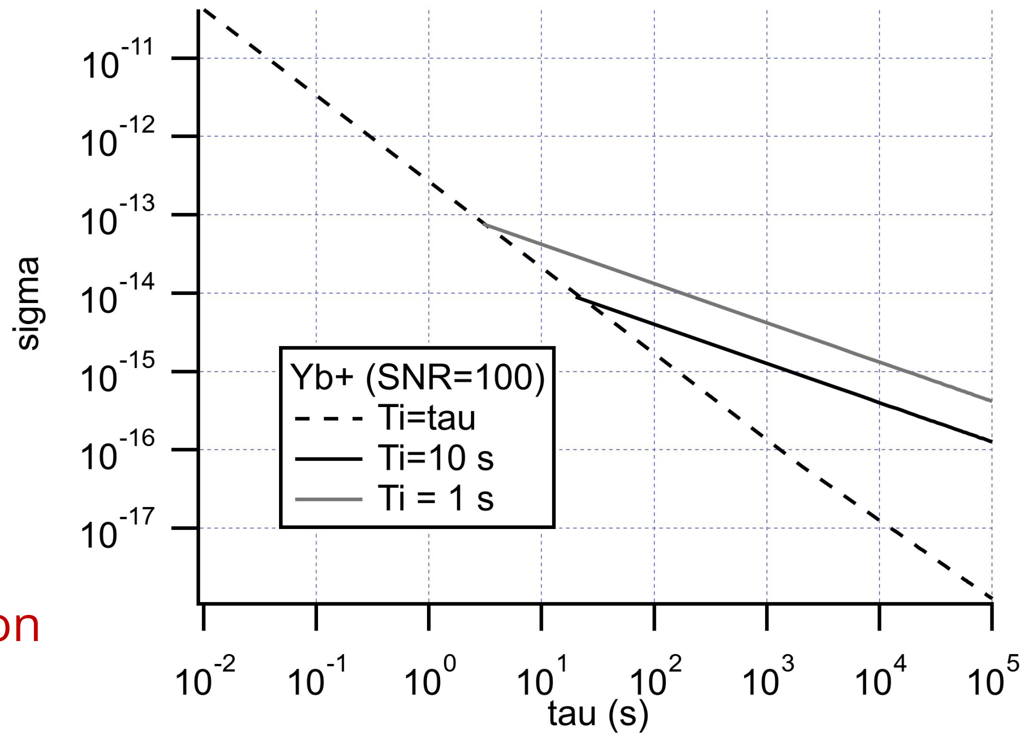
Image credit: Heather Partner Thesis

Physics: performance

Short term stability

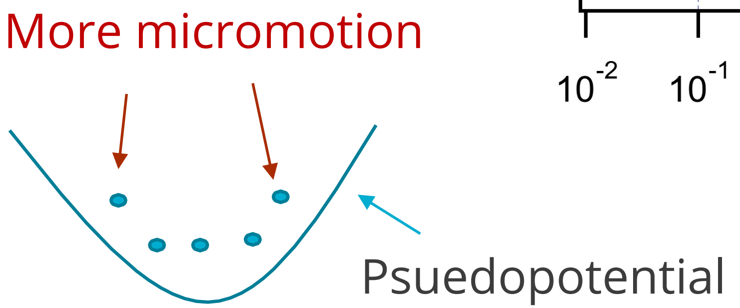
T_R = microwave interrogation time
ν_0 = Ground state hyperfine splitting (12.6 GHz)
T_c = Cycle time (T_R + laser interrogation time)
τ = integration time
SNR = Signal-to-noise ratio

$$\sigma = \frac{1}{2\,T_R \nu_0}\left(\frac{T_c}{\tau}\right)^{1/2}\frac{1}{SNR}$$



Long term stability

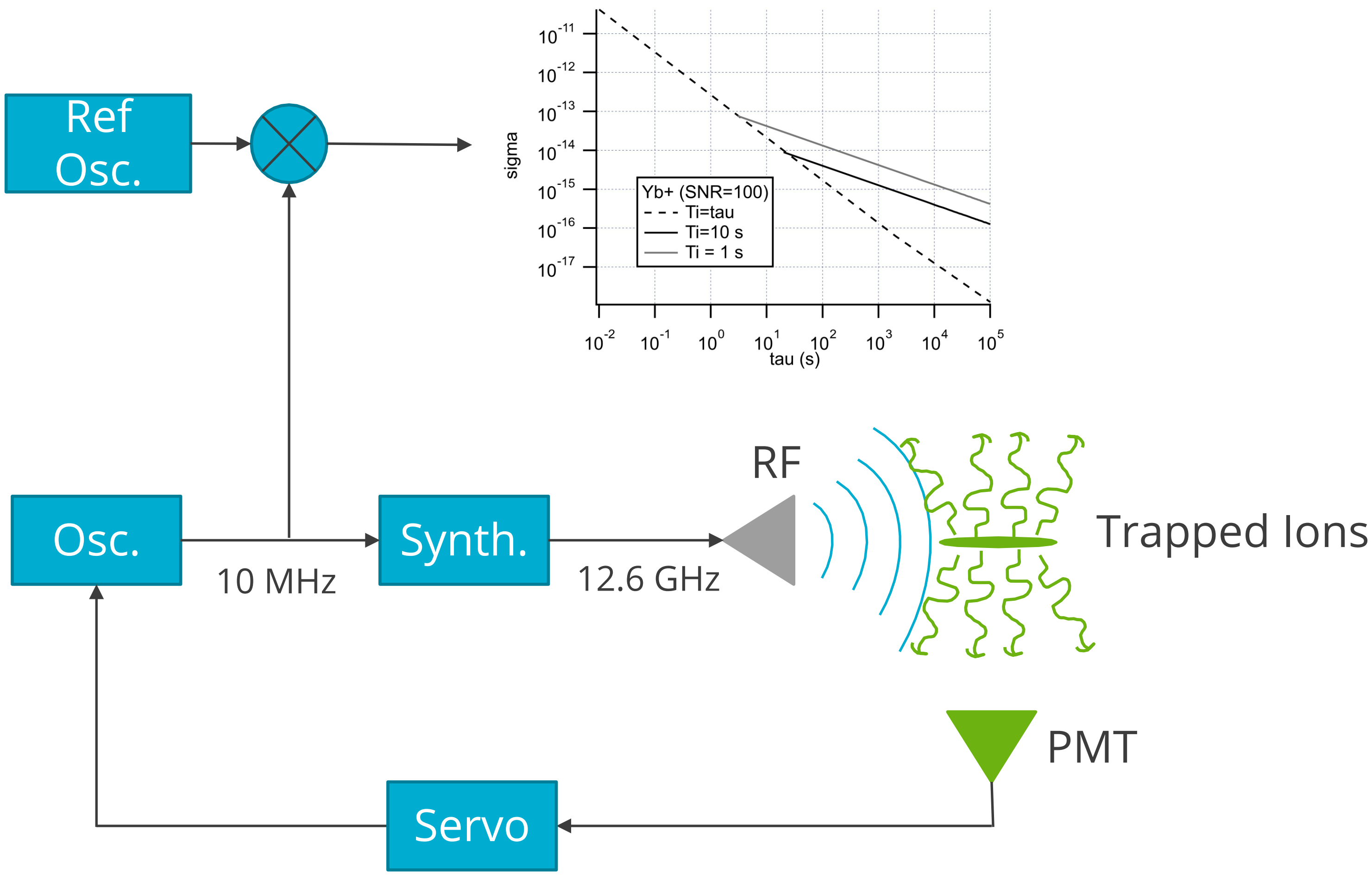
- 1st order doppler: **none** (ion cloud small compared to ν_0)
- 2nd order doppler: $\frac{\Delta\nu}{\nu} = -\frac{3kT}{mc^2}$ (~N due to space charge effect)
- First order Zeeman: **none**
- Non-linear Zeeman Effect: $\Delta\nu = 311\frac{Hz}{G^2}B_0$
- Buffer gas pressure: empirical



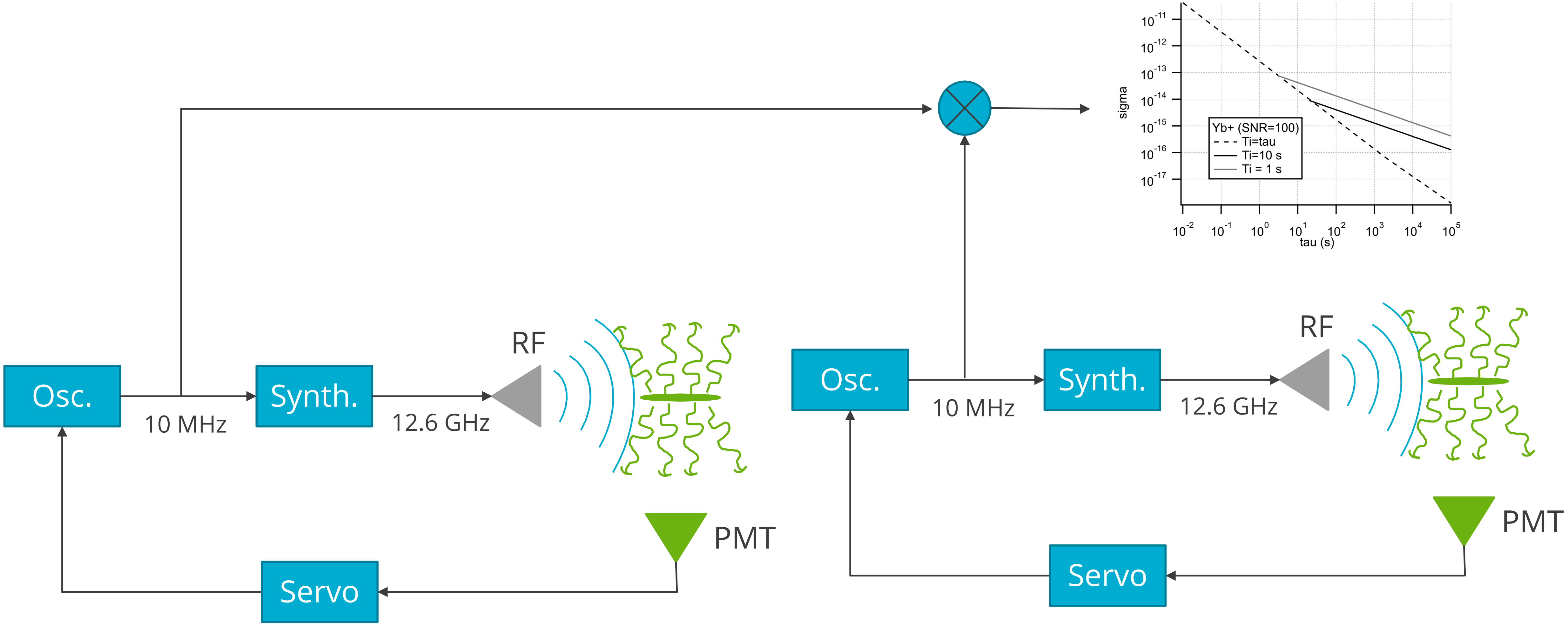
Setup

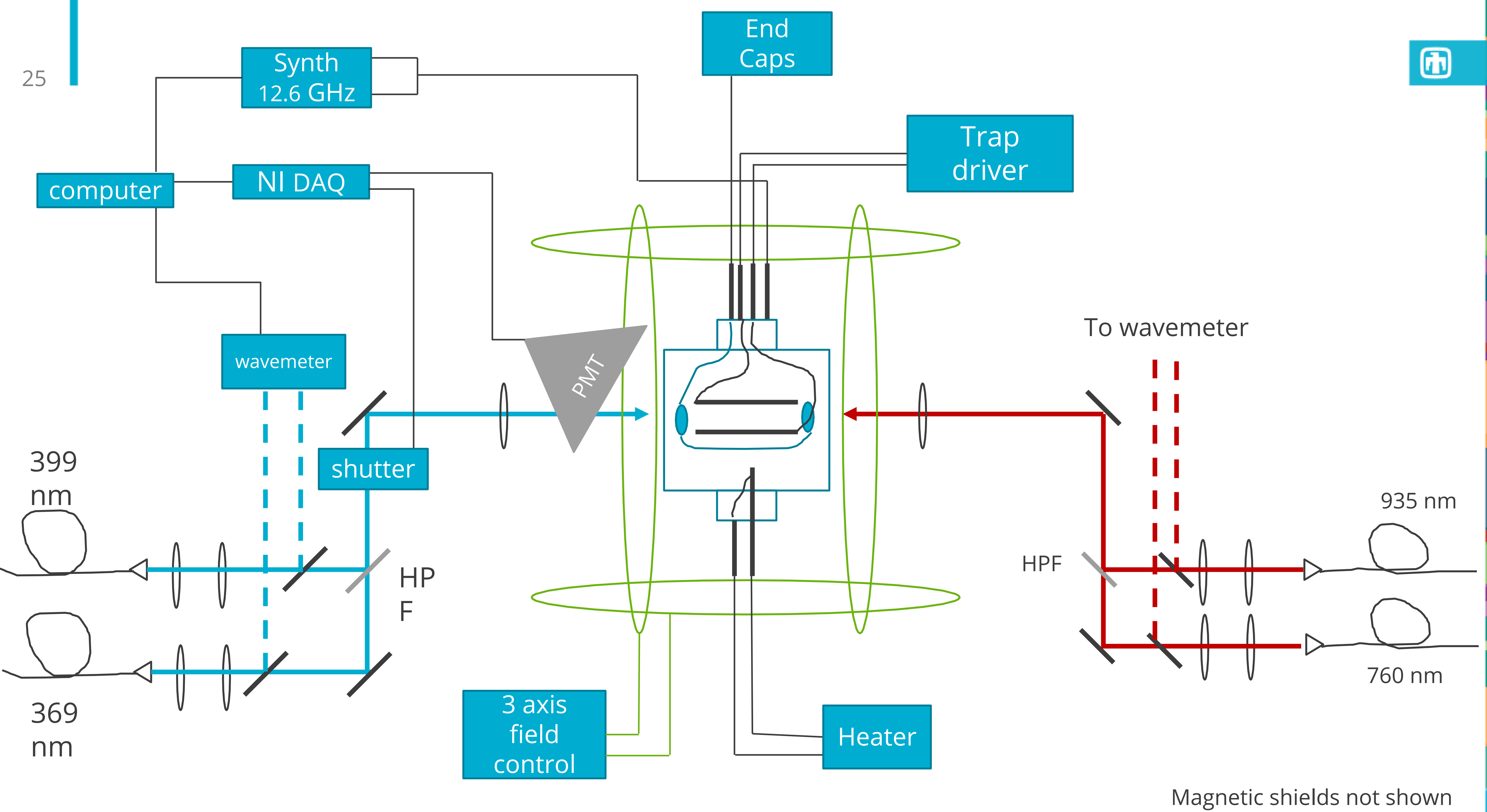
- What measurements are made and how?
- What does the apparatus look like?

Setup: single clock

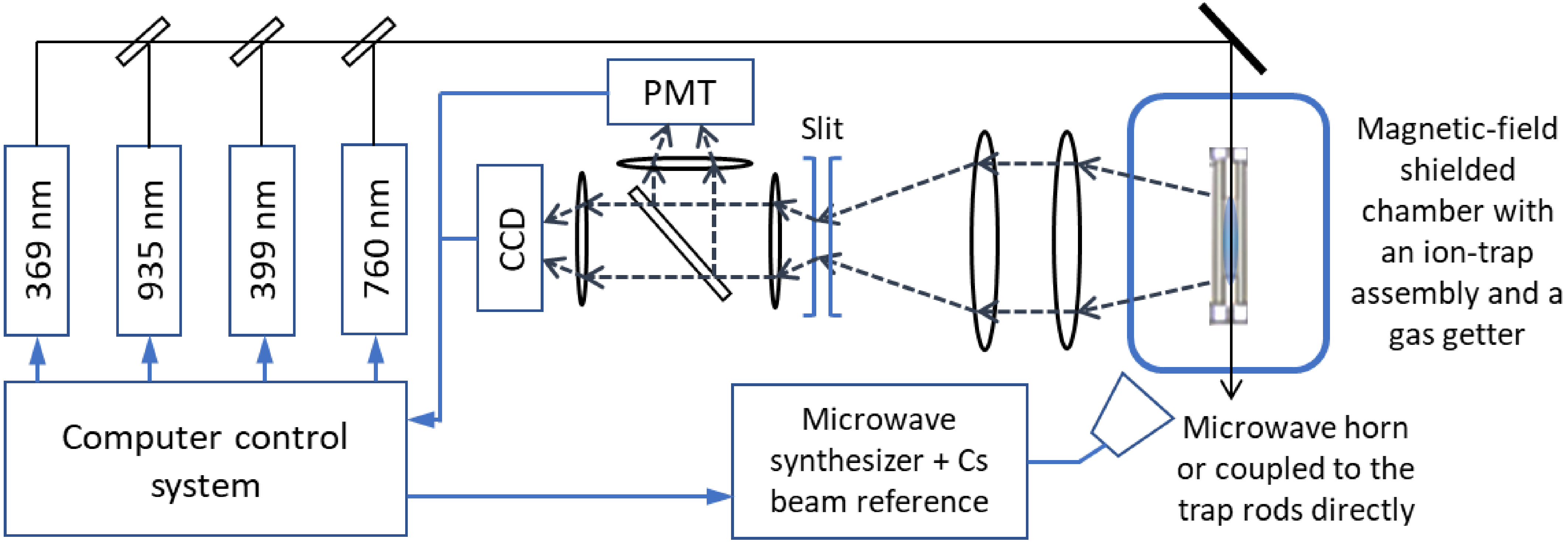


Setup: dual clock

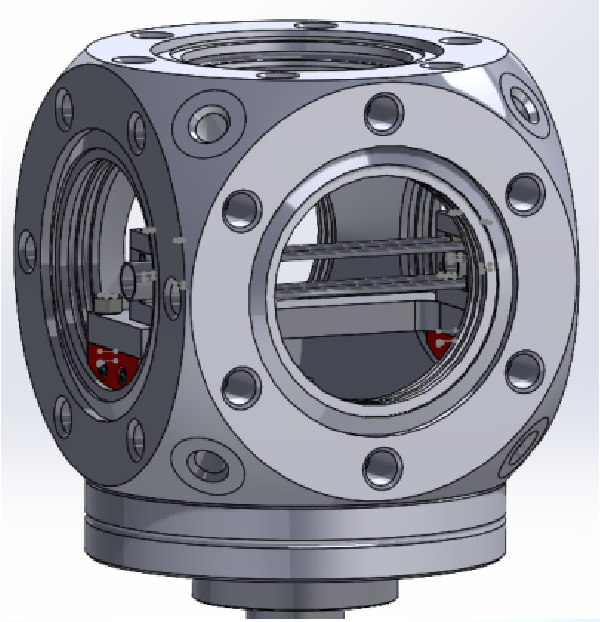


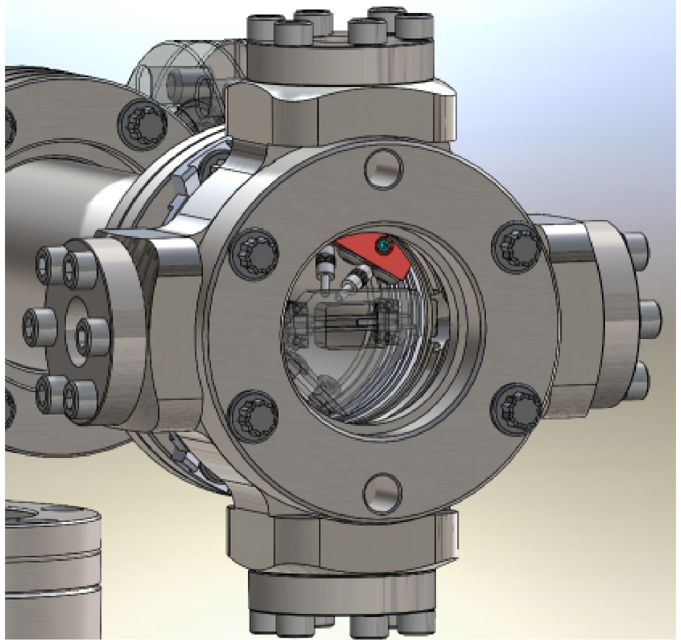

End Caps
Synth 12.6 GHz
Trap driver
computer
NI DAQ
wavemeter
PMT
To wavemeter
shutter
399 nm
935 nm
HPF
HP F
369 nm
760 nm
3 axis field control
Heater
Magnetic shields not shown

Setup


369 nm
935 nm
399 nm
760 nm
PMT
CCD
Slit
Magnetic-field shielded chamber with an ion-trap assembly and a gas getter
Computer control system
Microwave synthesizer + Cs beam reference
Microwave horn or coupled to the trap rods directly

Setup



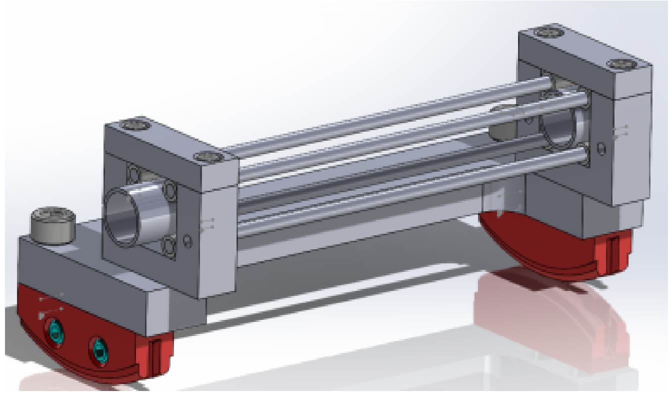


ACES-AMIC trap assembly

Rod spacing = 6.2 mm

End-cap spacing = 48 mm

Trap capacity: 10^6 – 10^7 ions

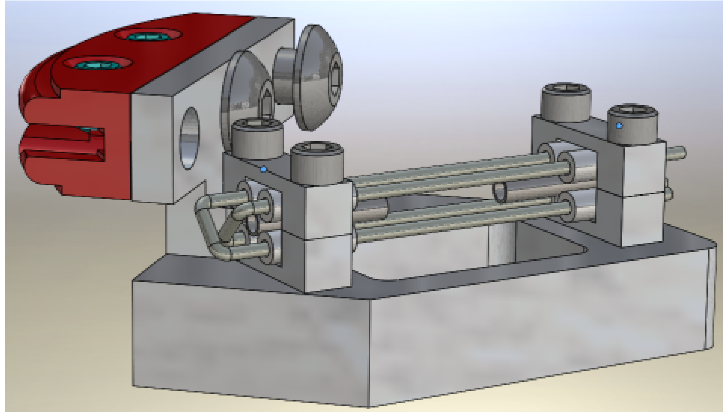


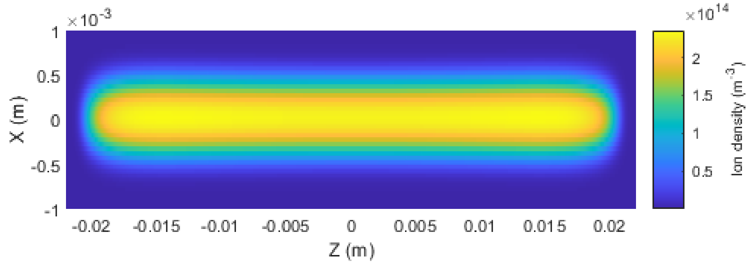
IMPACT trap assembly

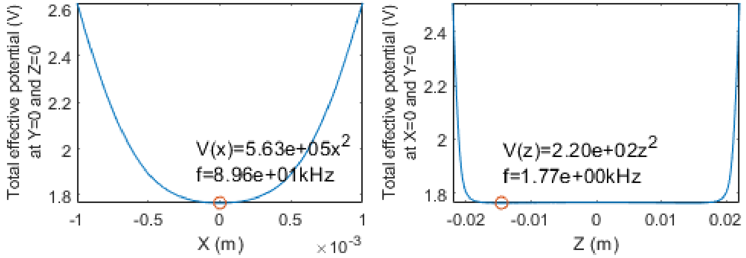
Rod spacing = 2 mm

End-cap spacing = 7 mm

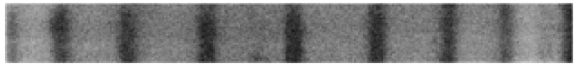
Trap capacity: 10^5 – 10^6 ions

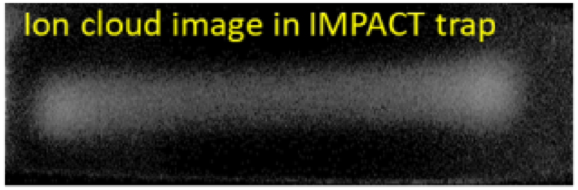


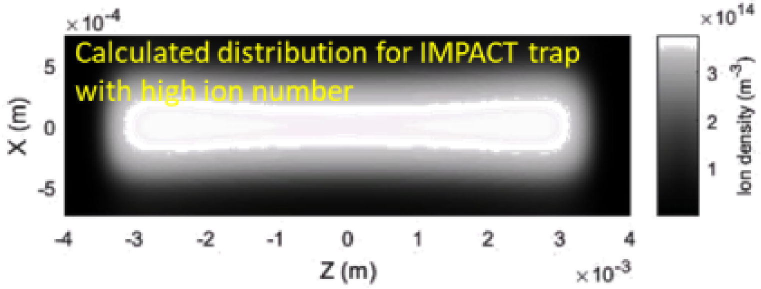




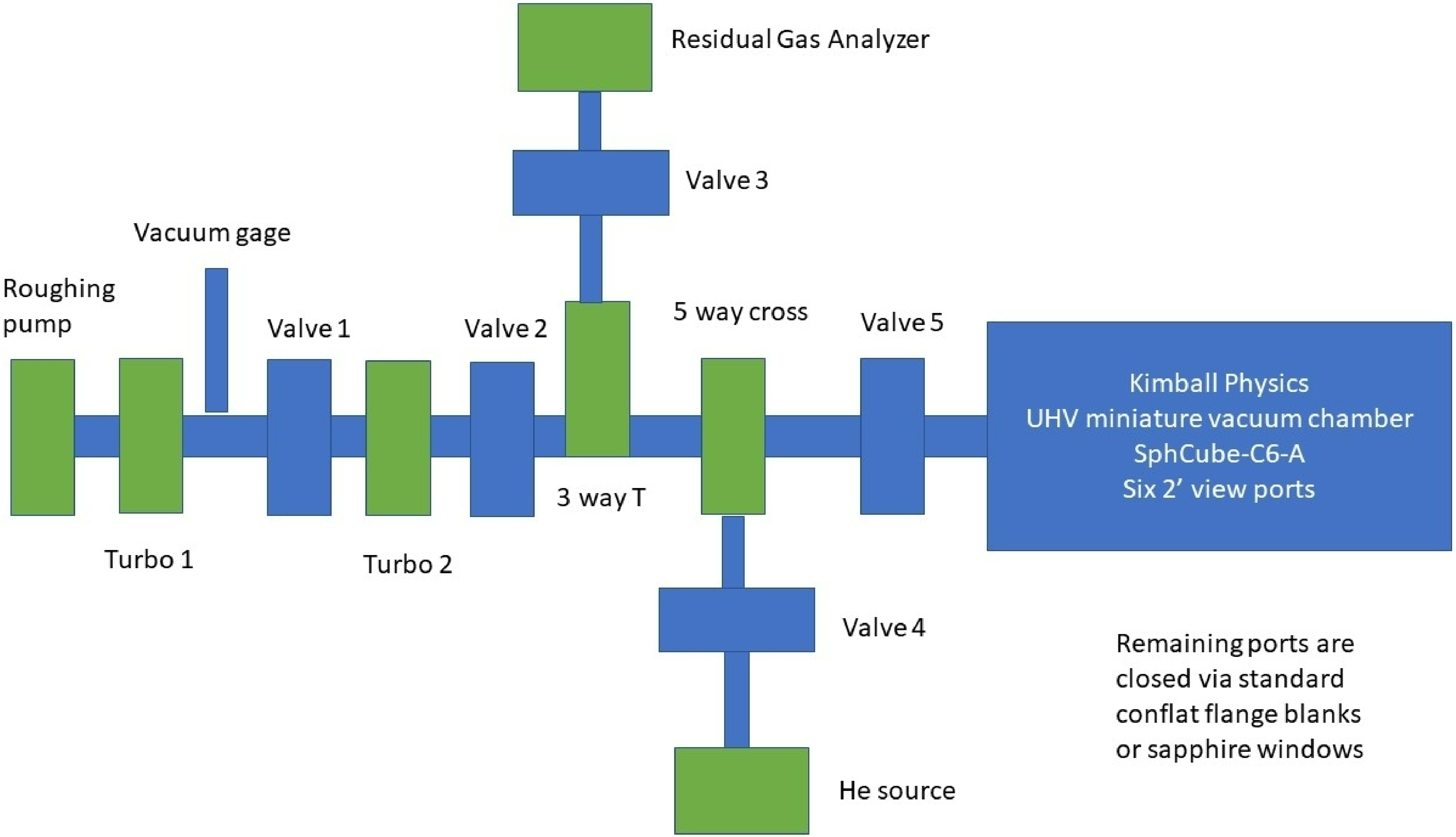
Calibration ruler: 1-mm spacing between adjacent lines







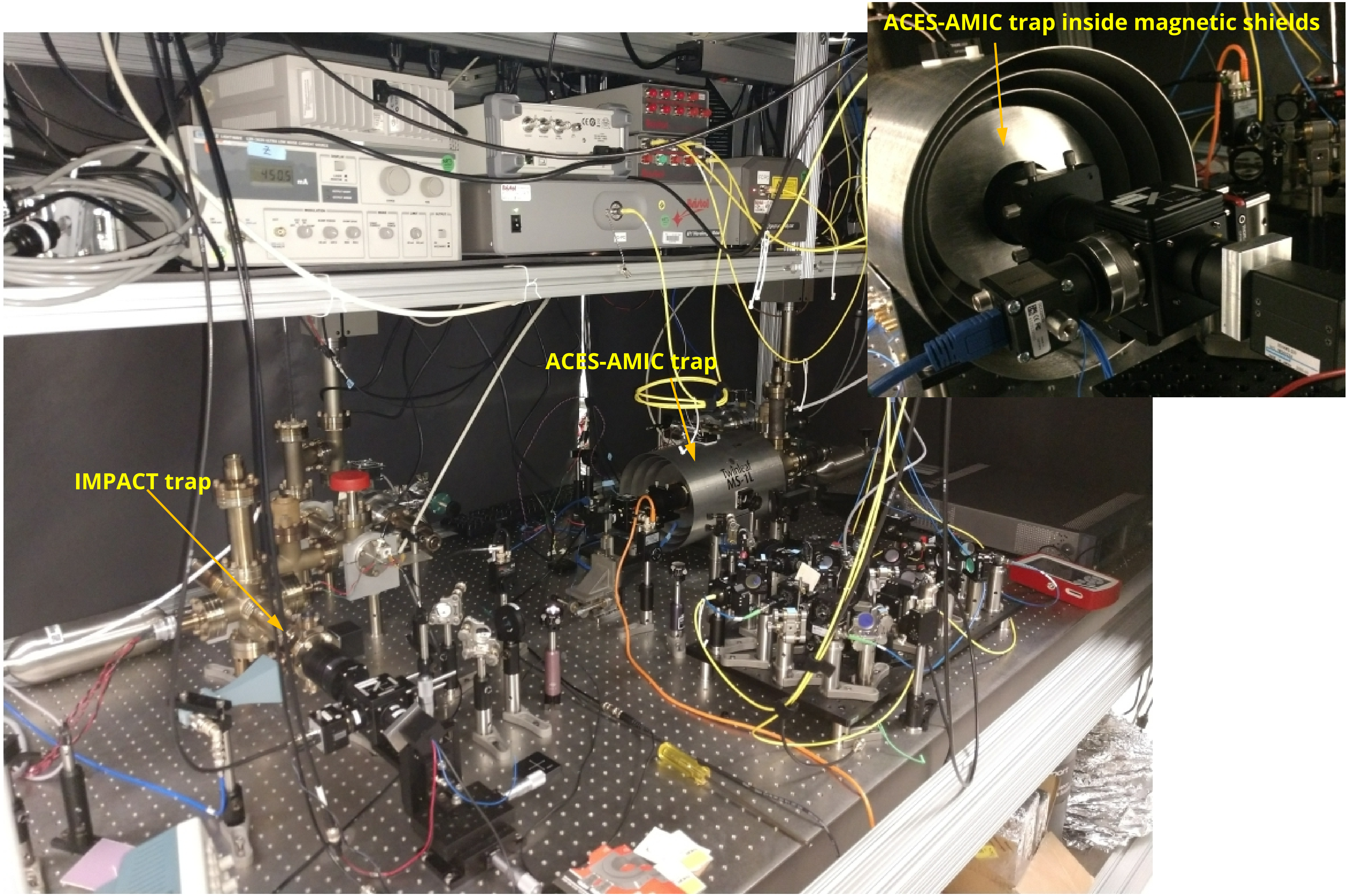
Setup: Vacuum system



Remaining ports are closed via standard conflat flange blanks or sapphire windows

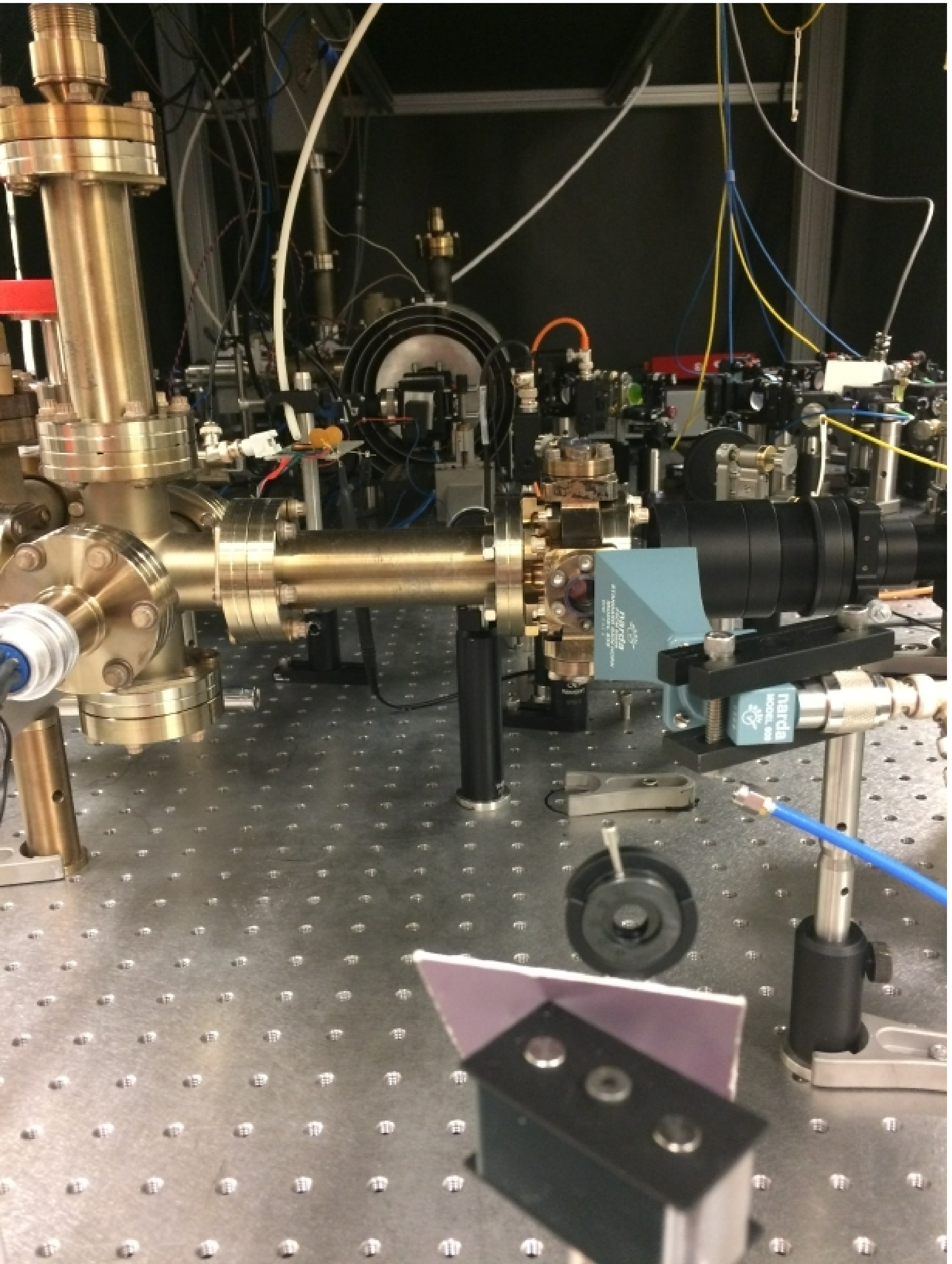
Setup

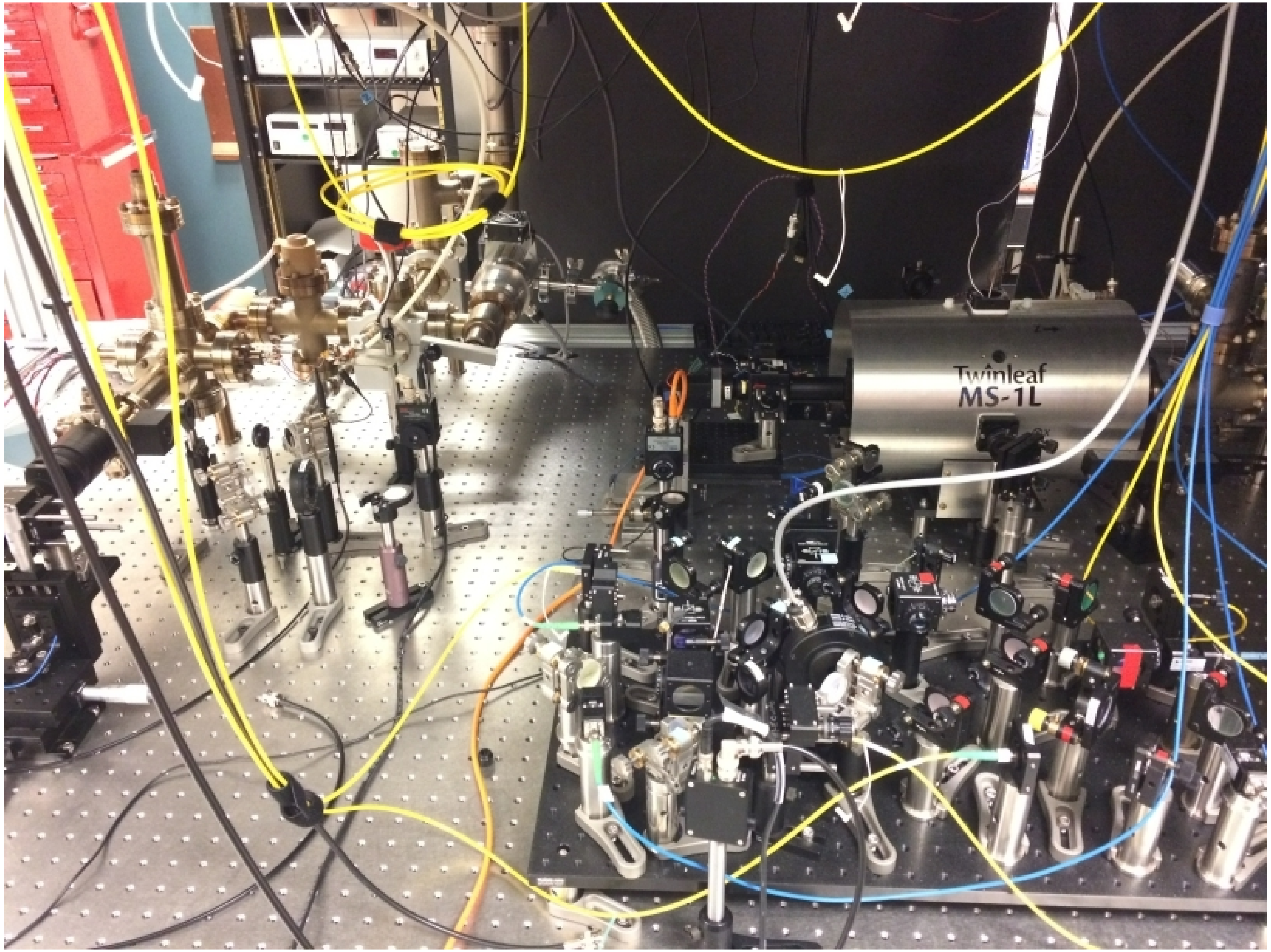
Toptica laser system for 369 nm, 399 nm, 760 nm, & 935 nm



Optical table with two Yb^{+} ion trapping setups as two independent ion clocks

Setup

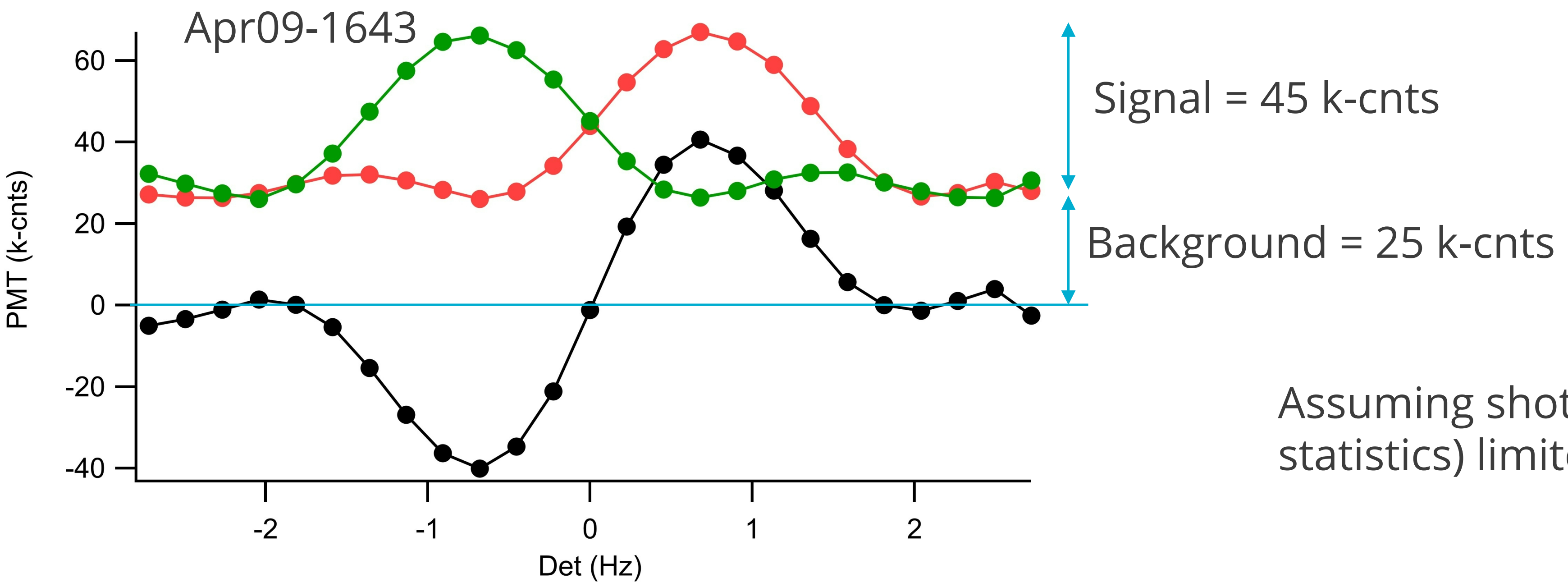




Results

- What is the short term performance of each clock?
- What limits short term performance?
- How do the clocks perform relative to one another?
- How does each clock depend on experimental parameters?

Results: ACES trap



Other settings
Background pressure: 300 pTorr
He buffer gas: 3.6 uTorr (ion gauge)
P369: 1.6 mW (not optimized)
P935: 3.4 mW (not optimized)
P760: 0 mW (blocked)
Laser beam waists: ~ 1 mm (estimate)
Gate time: 25 ms
Field Strength: ~400 mG
RF drive voltage: 950 Vpp
End-cap voltage: +11V
Ion lifetime: > 1 week
Voltage divider: 102
Agilent freq: 12.642812743 GHz
Agilent power: -38 dBm

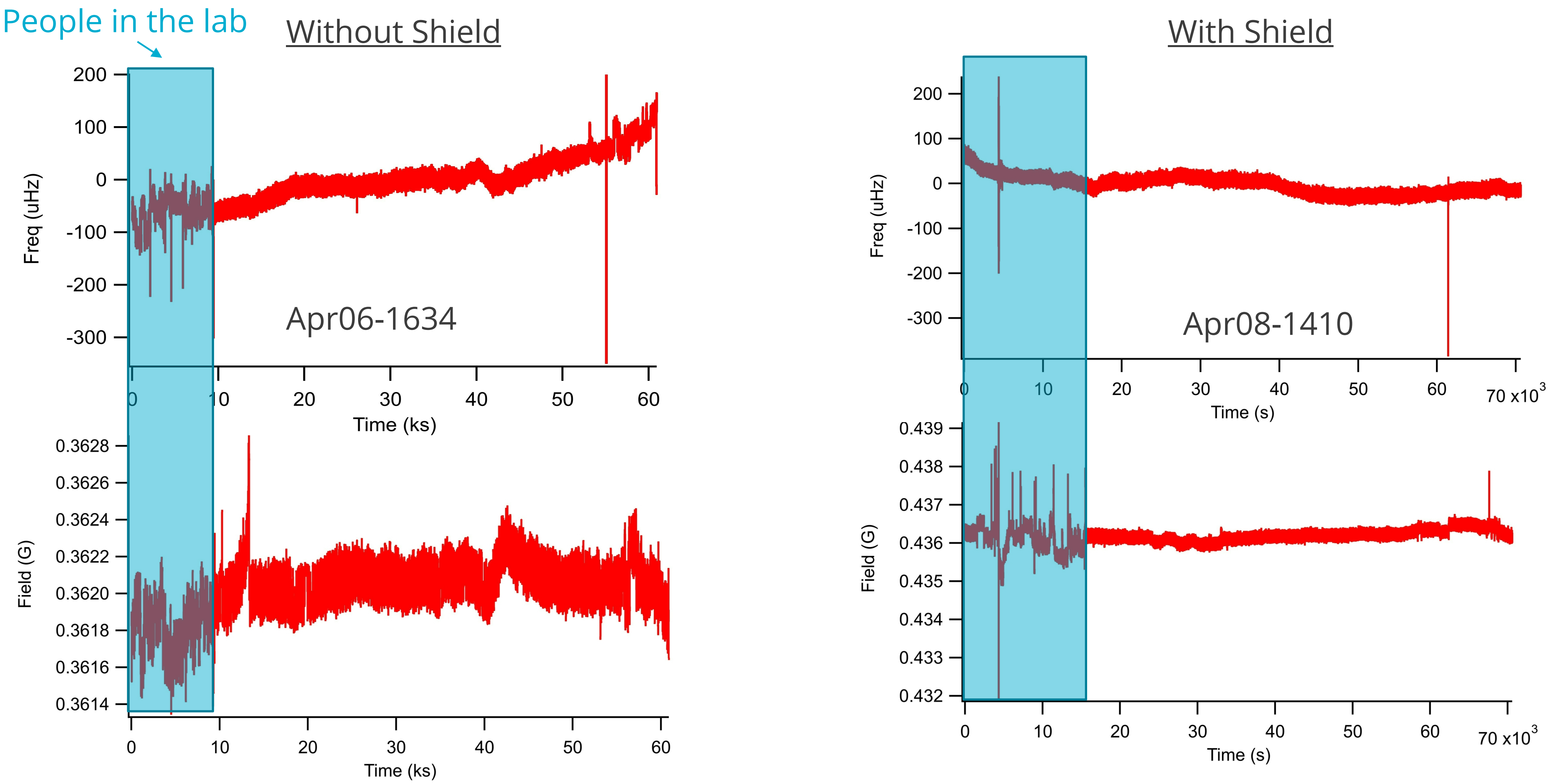
Assuming shot noise (photon counting statistics) limited then…

T_R = microwave interrogation time = 600 ms
ν_0 = Ground state hyperfine splitting = 12.6 GHz
T_c = Cycle time (T_R + laser interrogation time) = 700 ms
τ = integration time
SNR = Signal-to-noise ratio

$$SNR = \frac{S}{N} = \frac{S}{(S+B)^{1/2}} = \mathbf{170}$$

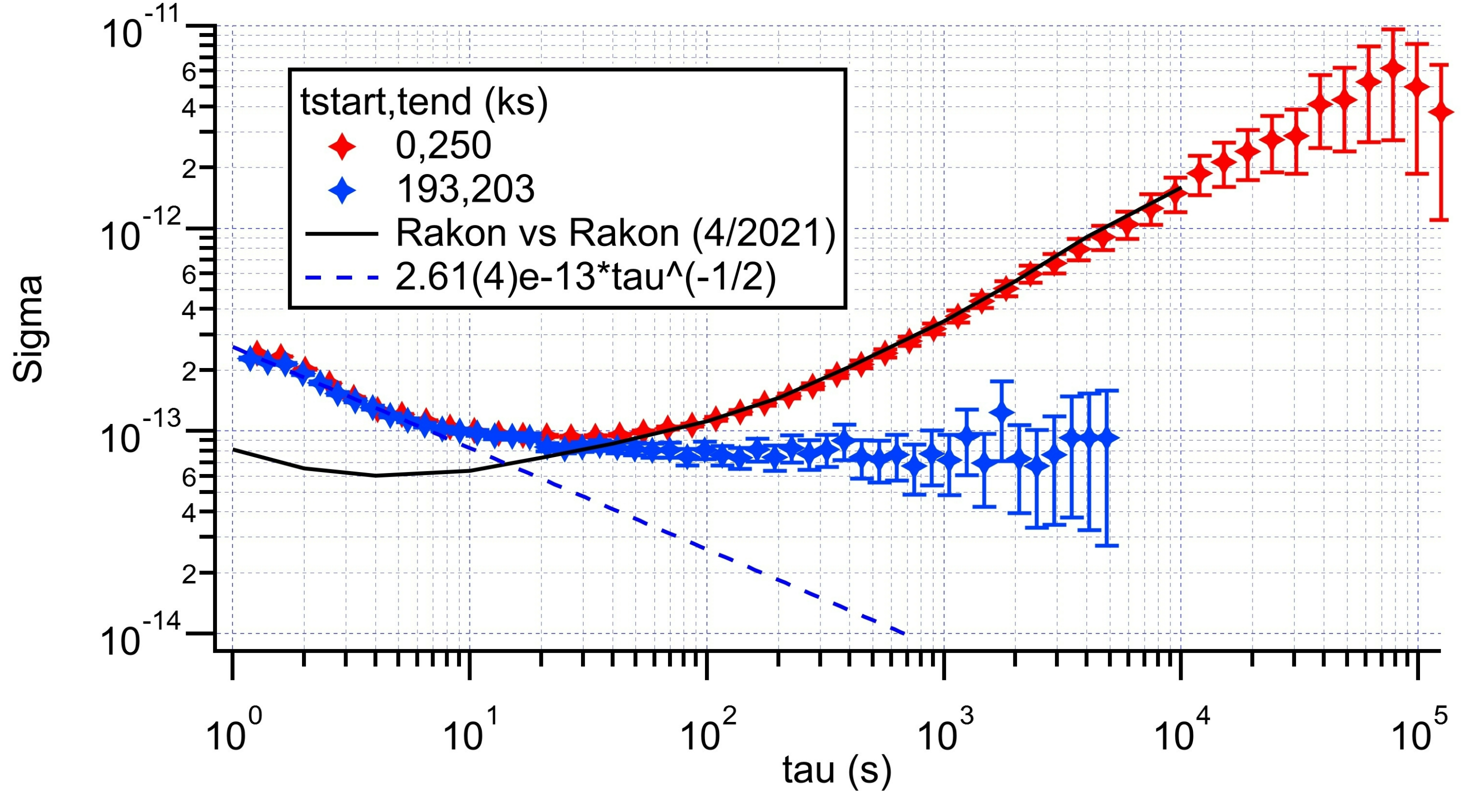
$$\sigma = \frac{1}{2\, T_R \nu_0}\left(\frac{T_c}{\tau}\right)^{1/2} \frac{1}{SNR} = \mathbf{3.3 \times 10^{-13}\, \tau^{-1/2}}$$

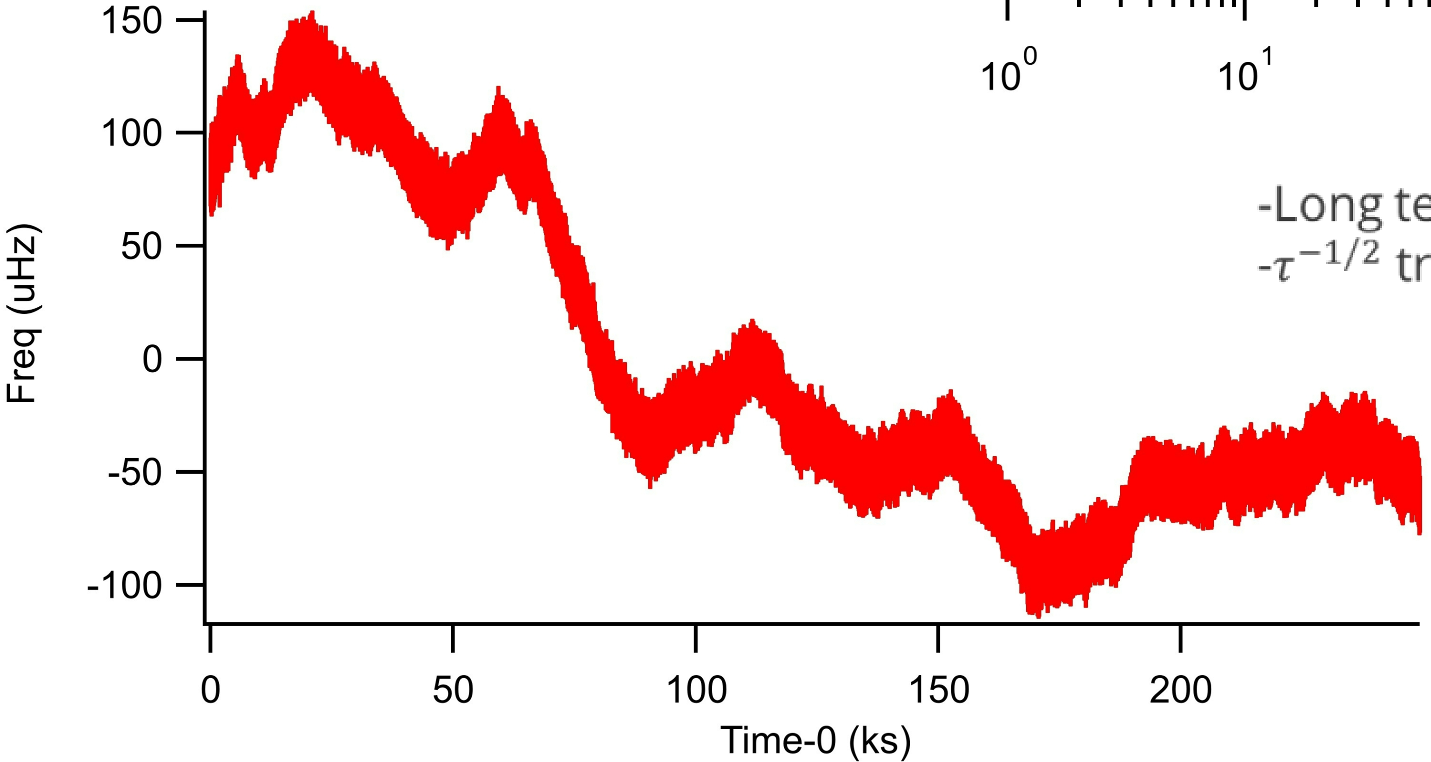
Results:Influence of Magnetic Shield (ACES)



The magnetic shield allows me to take “good” data while people are working in the lab

Results: ACES

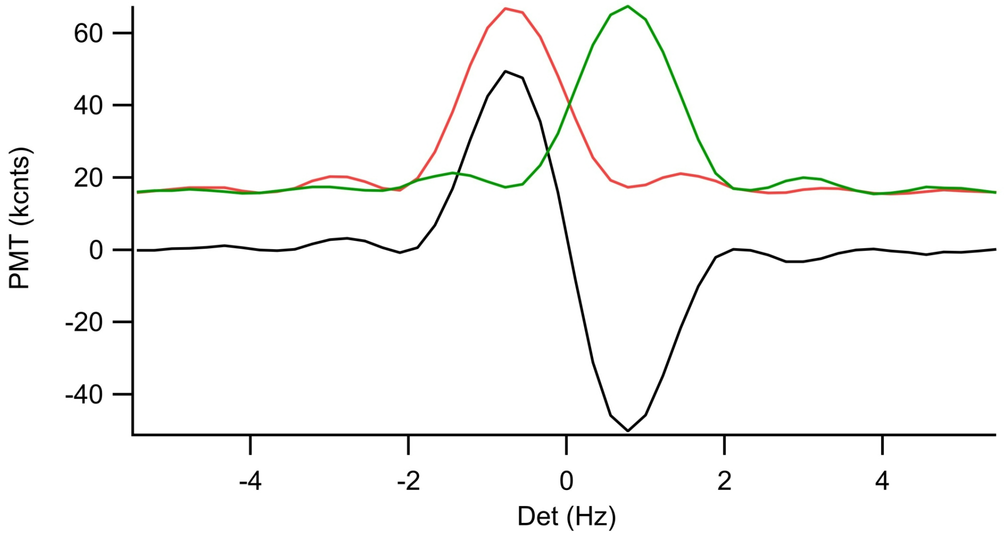


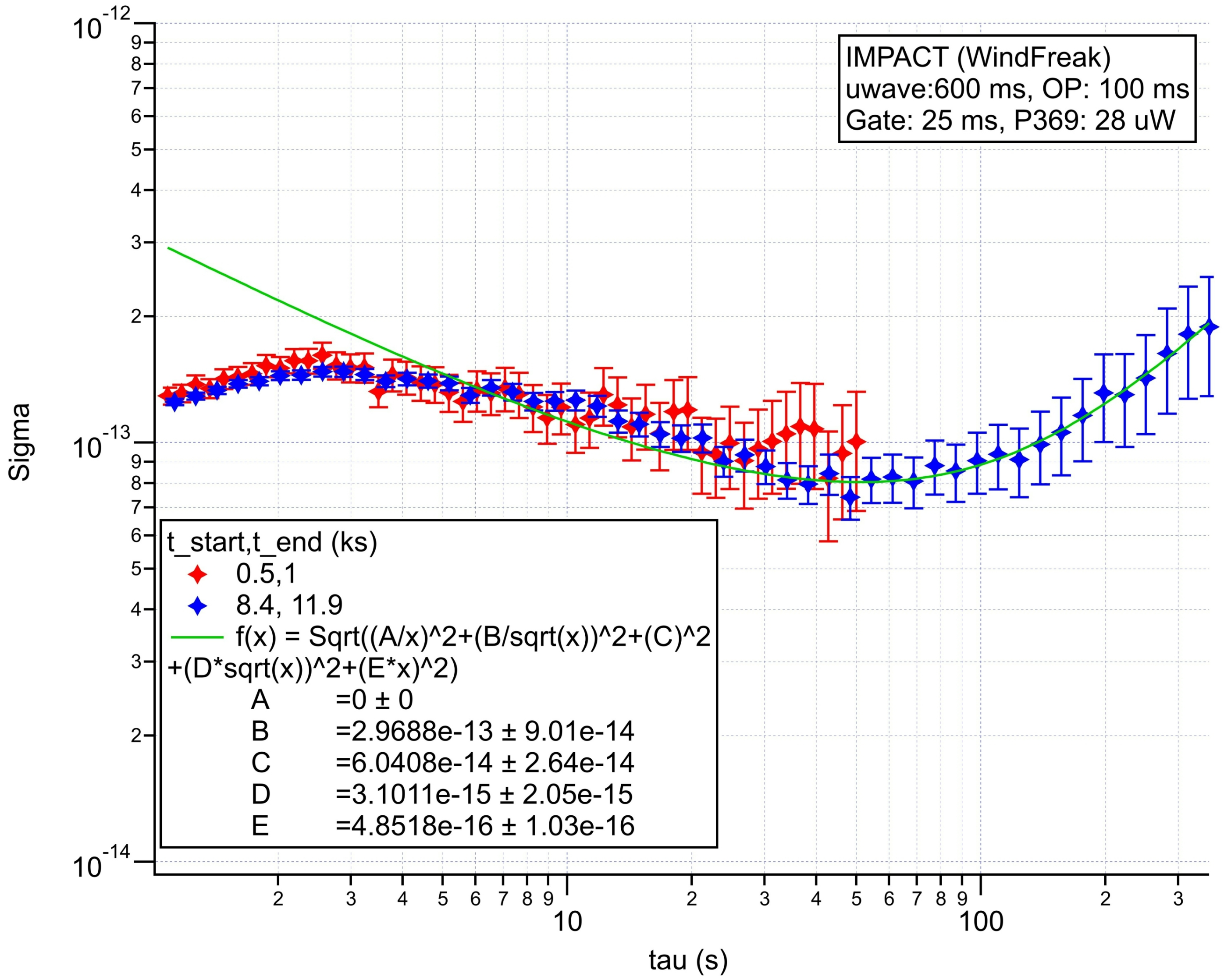


-Long term stability limited by reference oscillator

-$\tau^{-1/2}$ trend similar to SNR-limited calculation

Results: short term performance (IMPACT)



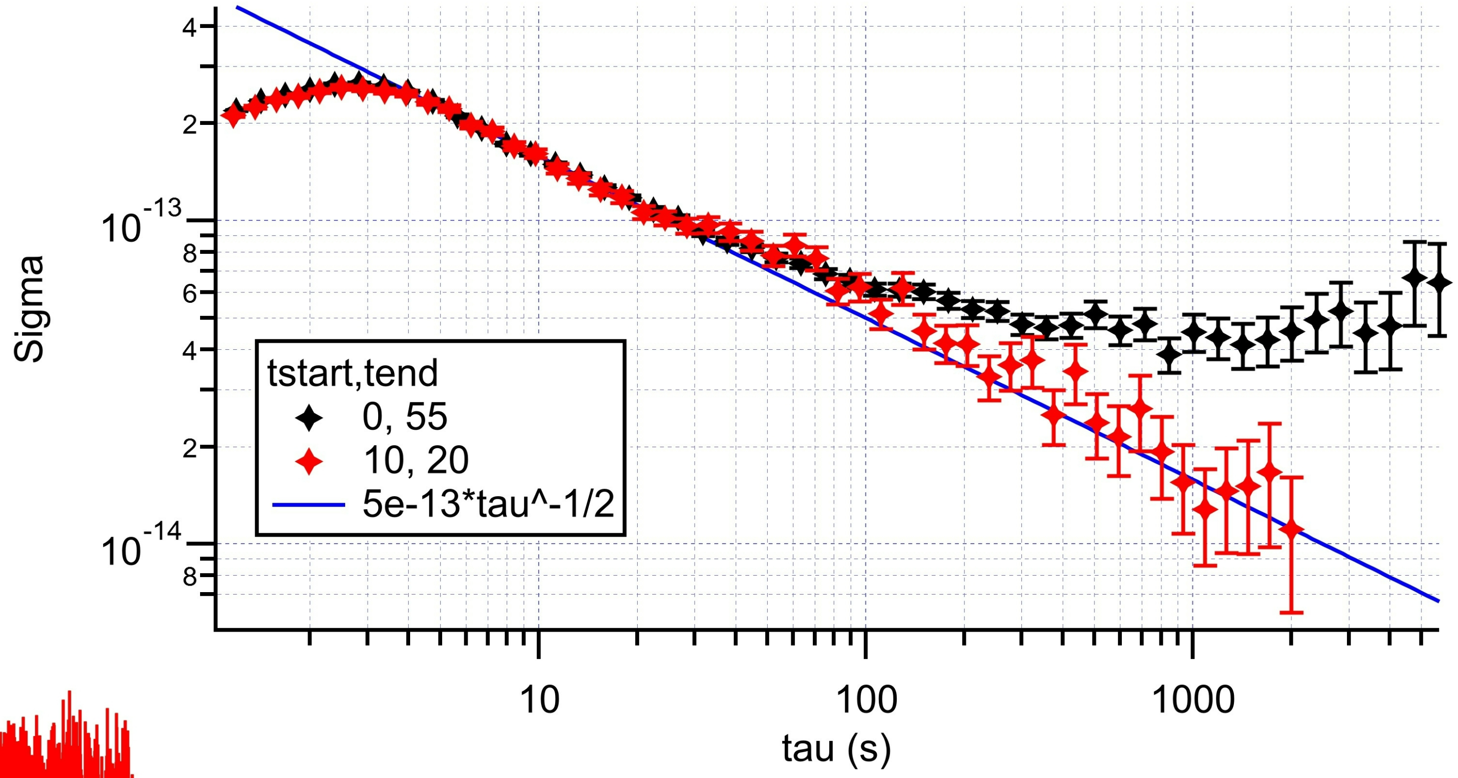


-Long term stability limited by reference oscillator

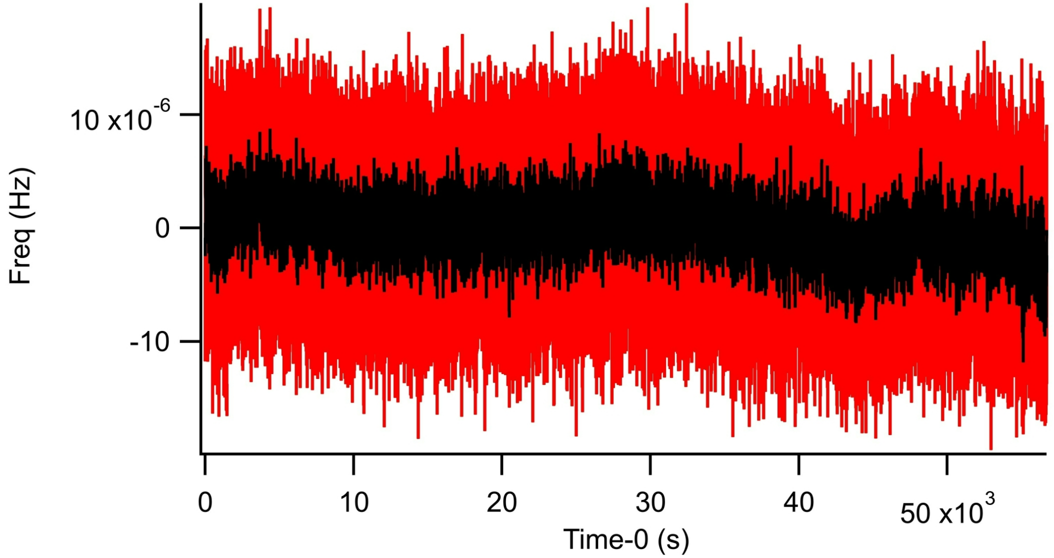
-$\tau^{-1/2}$ trend similar to SNR-limited calculation

-similar SNR despite much smaller trap volume (unable to collect photons with high SNR from periphery of ACES trap)

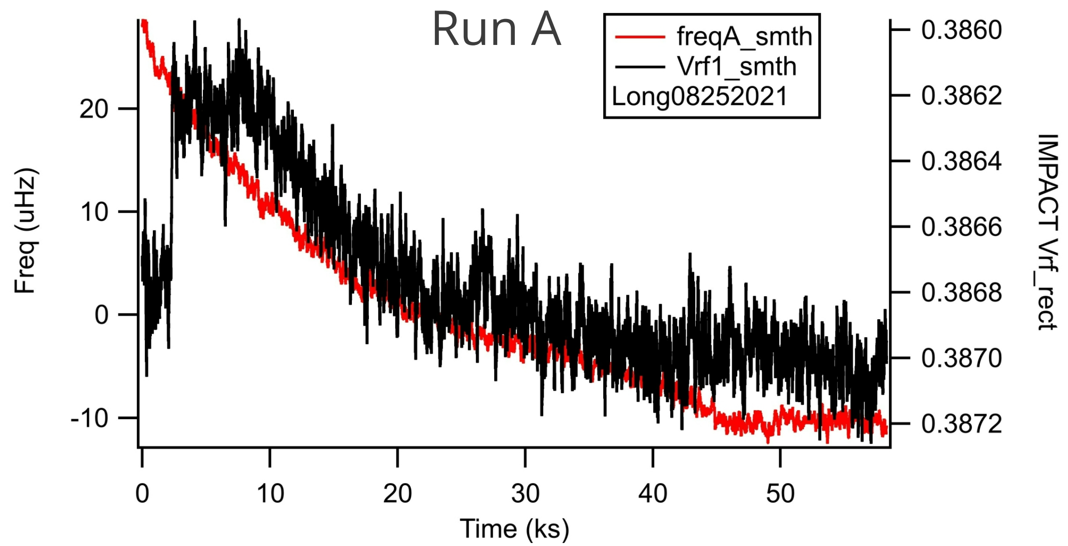
Results: long term performance (ACES vs IMPACT)

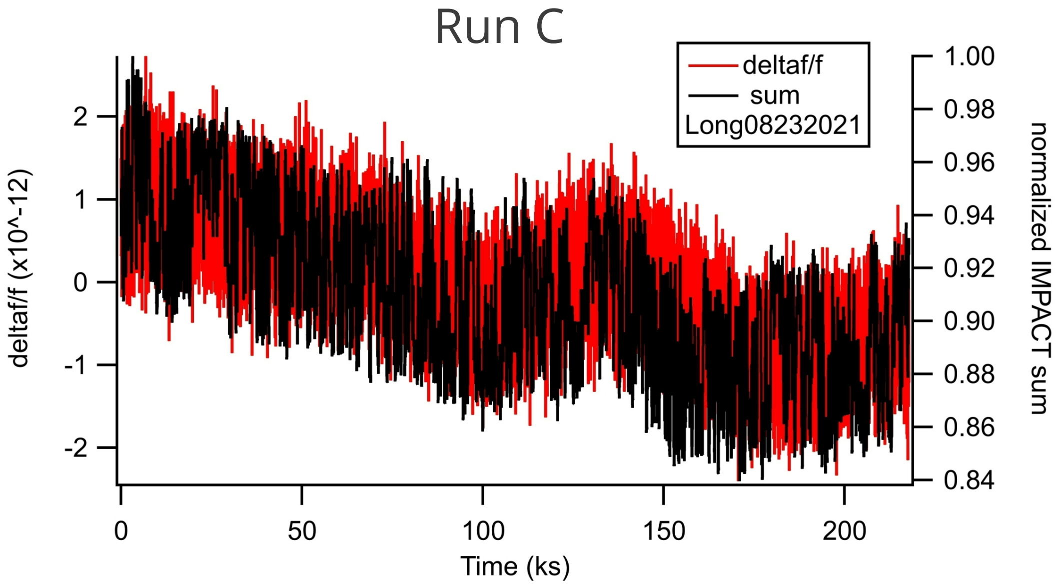


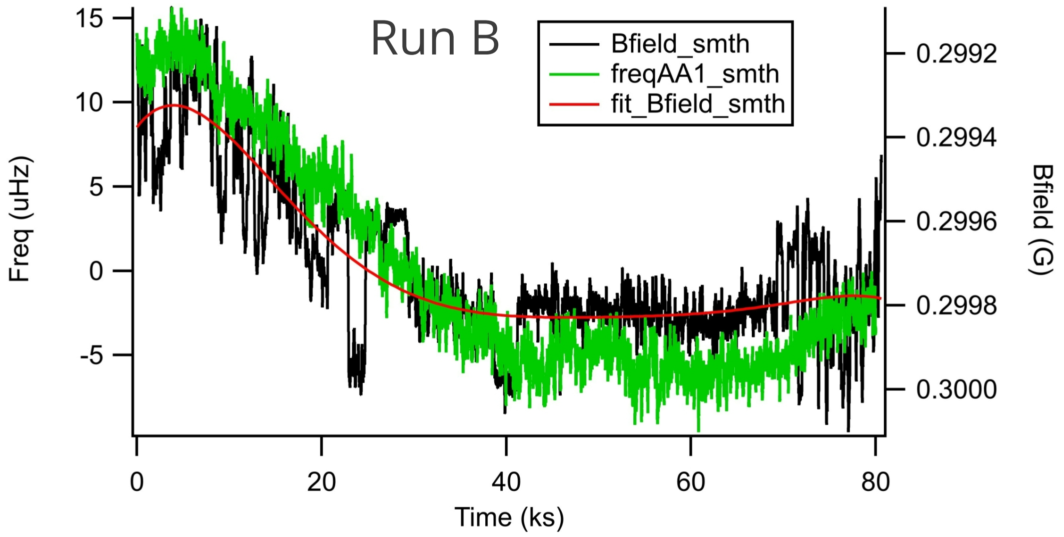
Clock frequency difference (red)
and its average (black)



Results: long term performance



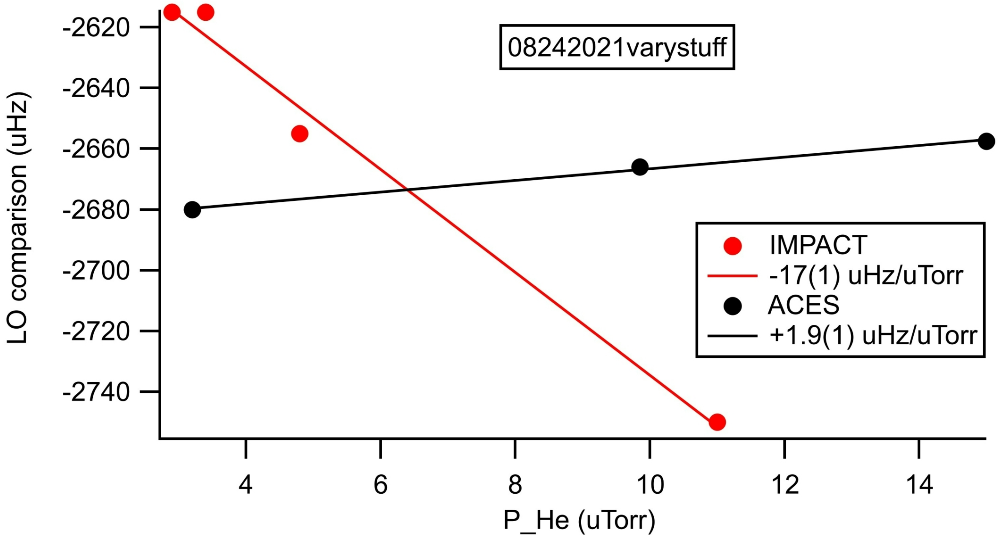


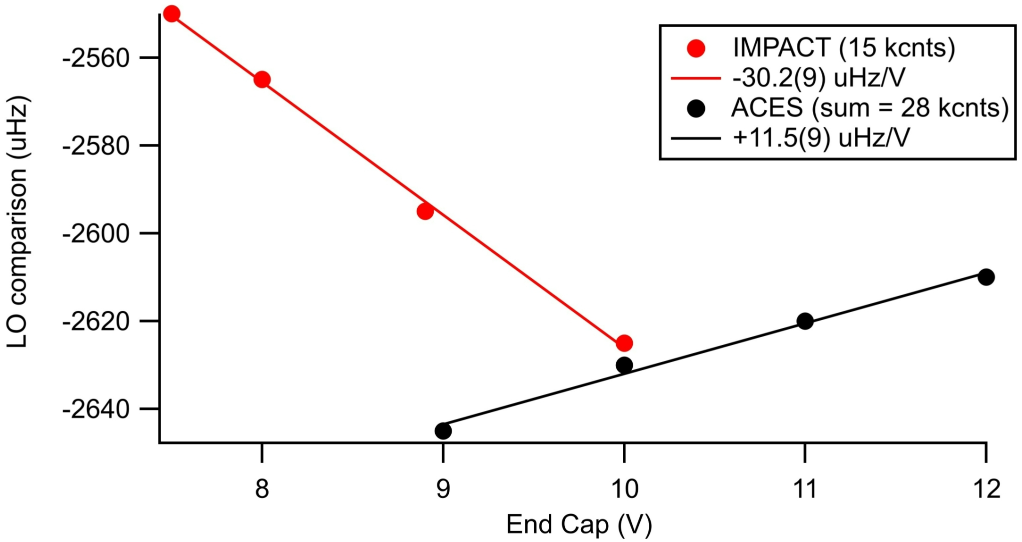


Parameters that have appeared correlated with frequency drift:

- V_RF [run A]
- Ambient B-field [run B]
- Ion signal ("sum") [run C]

Results: long term performance





These dependencies are more than and order of magnitude greater than those in the literature.

Possible explanation: High order B-field gradients. End cap voltage and He pressure change the ion cloud position.

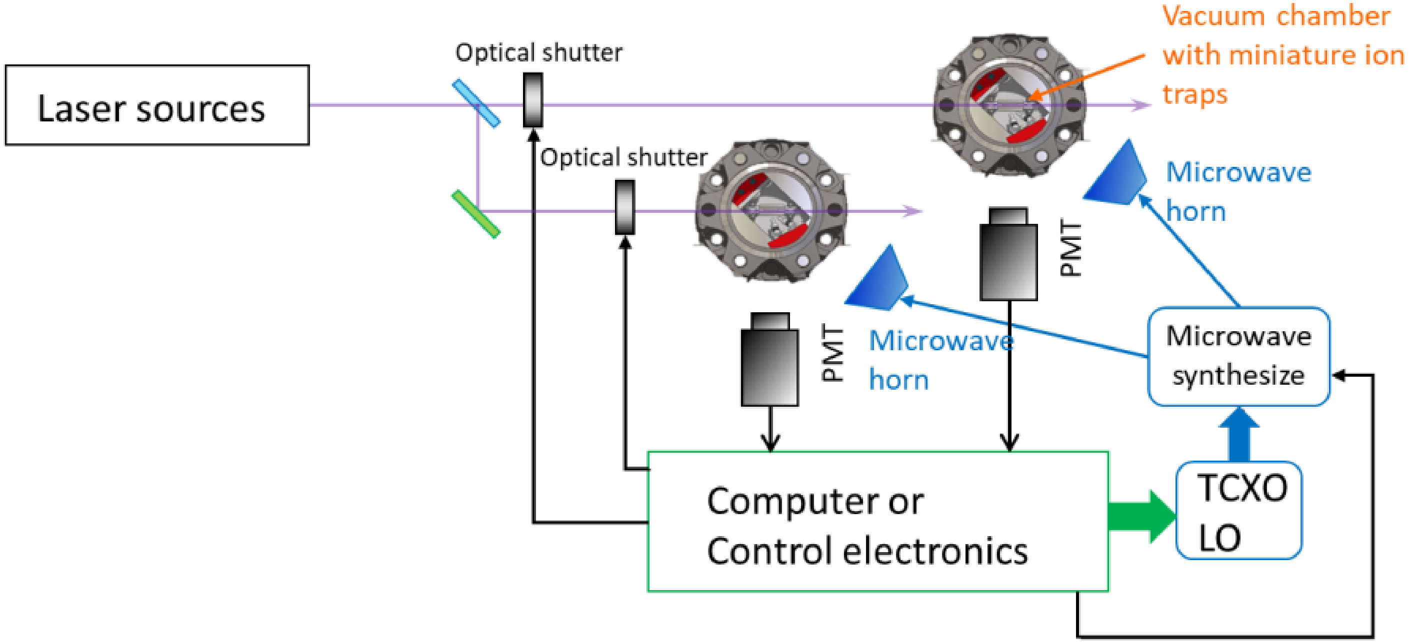
Plan to repeat these measurements at various bias field values.

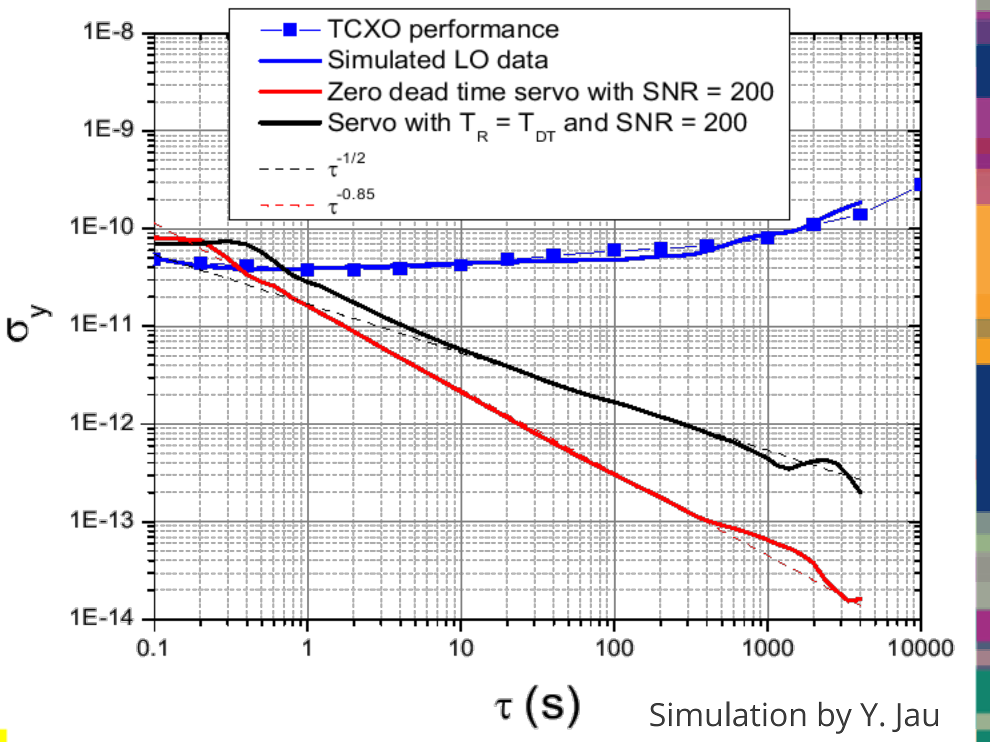
Future

- Reduce long term drift
  - Use ions to stabilize bias field
  - Reduce magnetic gradients (no stainless steel!)
- Run clock with developed DFB 369 nm laser
- Zero dead time clock

Future: zero dead time

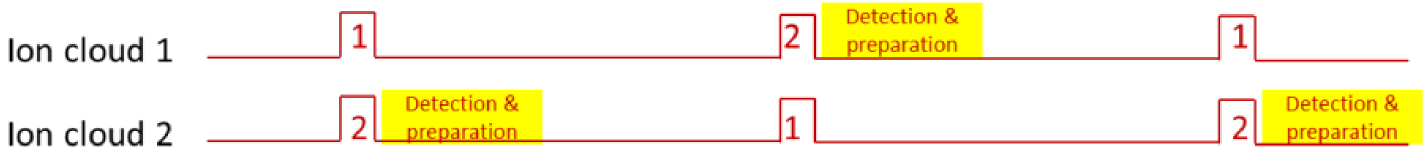
We can in principle use two ion traps to achieve complementary clock interrogations to cover the deadtime due to the signal detections.





Simulation by Y. Jau

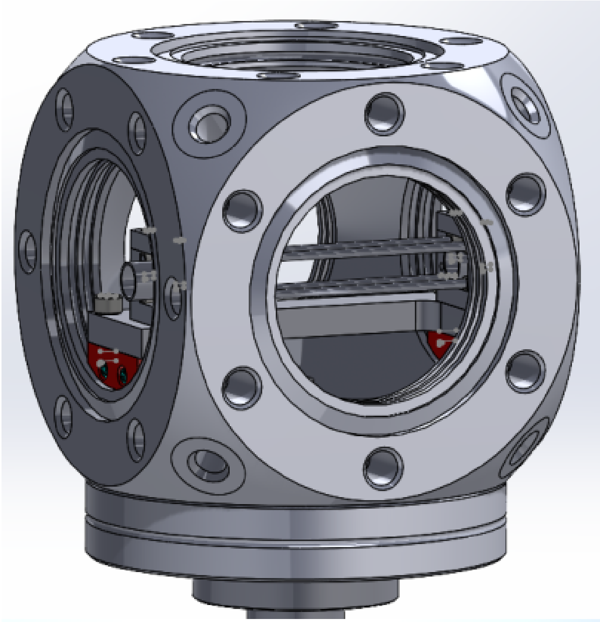
Using Ramsey spectroscopy for probing clock resonances from two ion clouds

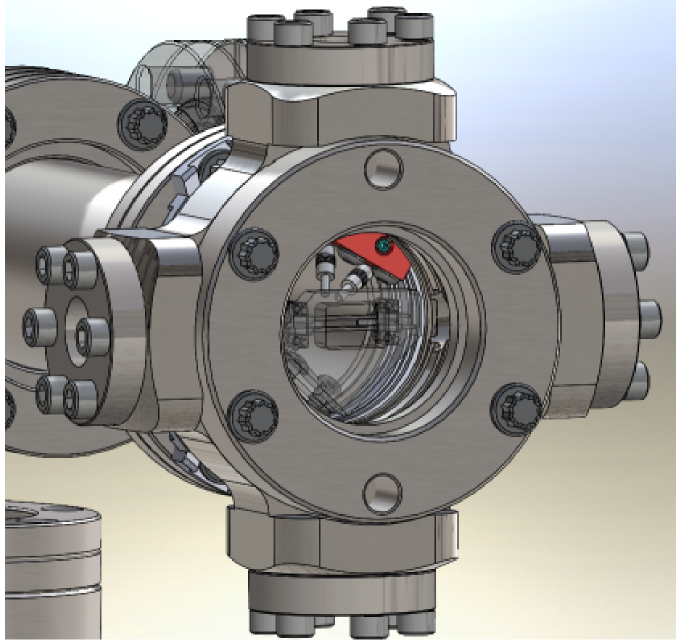


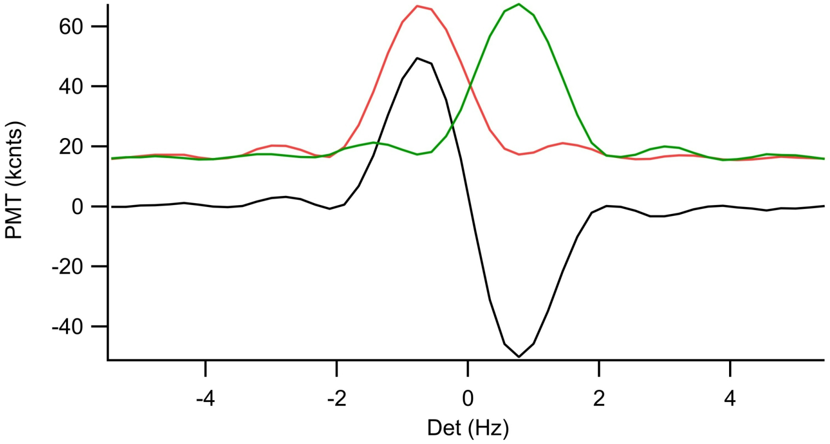
Pulses are microwave $\pi/2$ pulses.

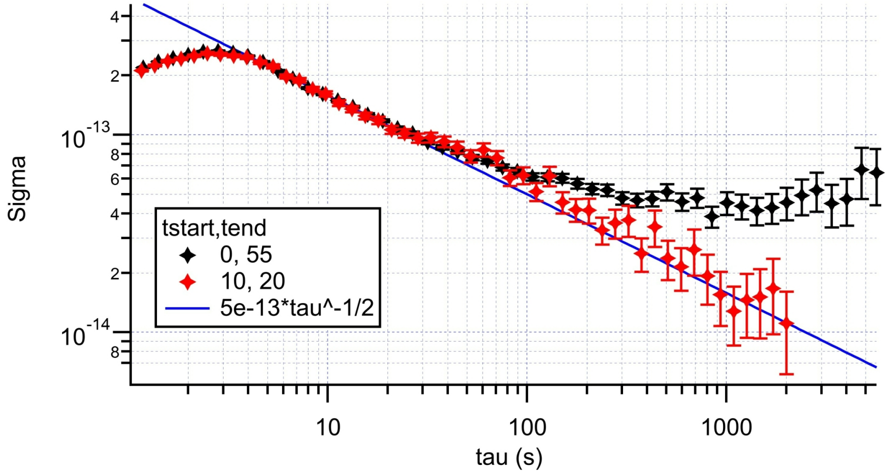
Replace UXO with TCXO and second ion trap ➡ lower power, smaller size, same long term stability

Conclusion



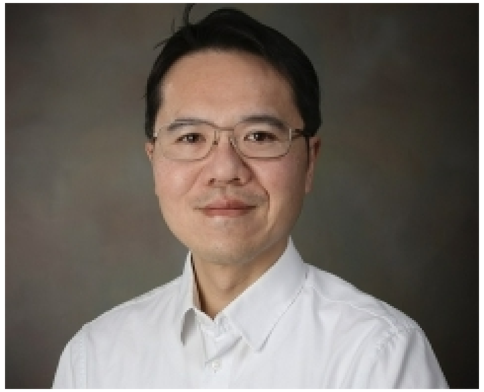






Funding:

Principal investigators:



Yuan-Yu Jau and **Peter Schwindt** (SNL)