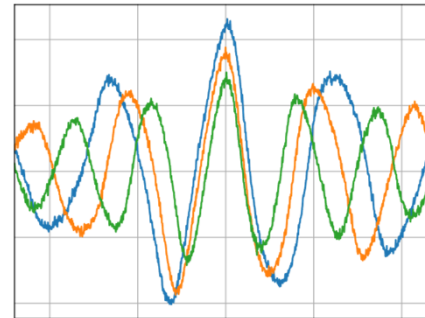
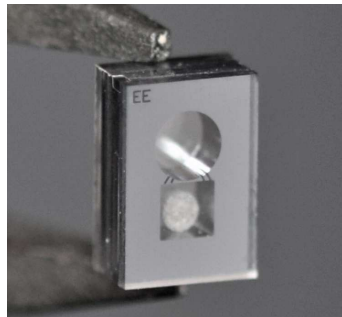


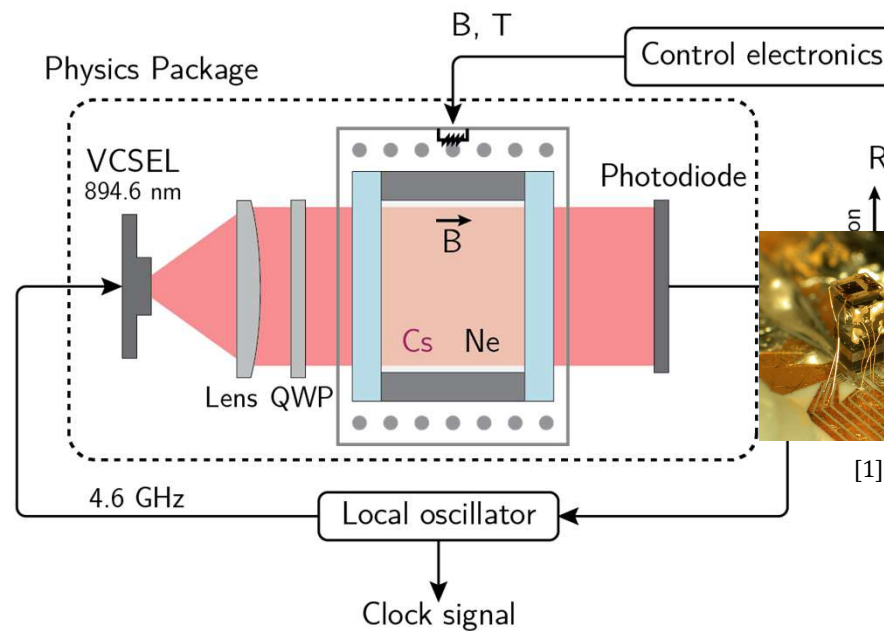


# Light-shift measurements in a microcell CPT clock using symmetric autobalanced Ramsey spectroscopy



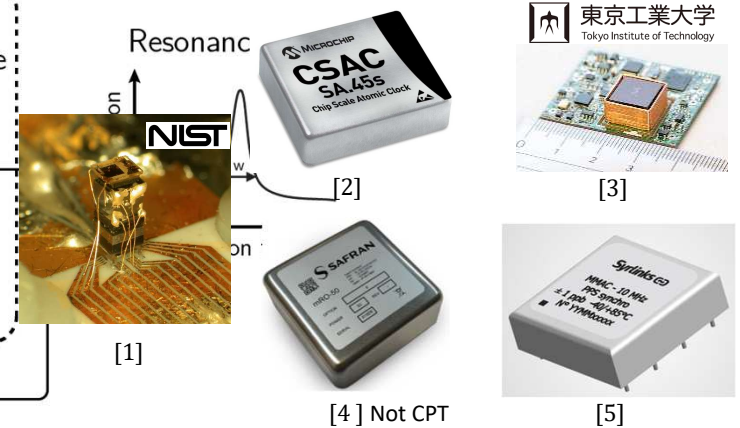
**Carlos M. Rivera-Aguilar**, Moustafa Abdel Hafiz, Jean-Michel Friedt,  
Nicolas Passilly and Rodolphe Boudot.

# Microwave CPT-based CSACs



## Typical specifications of CSACs

15-20 cm<sup>3</sup>  
100-400 mW  
10<sup>-10</sup> at 1 s, 10<sup>-11</sup> at 1 day



## Limitations:

Short-term stability: VCSEL FM noise

Long-term stability: **Light-shifts** and collisional shifts

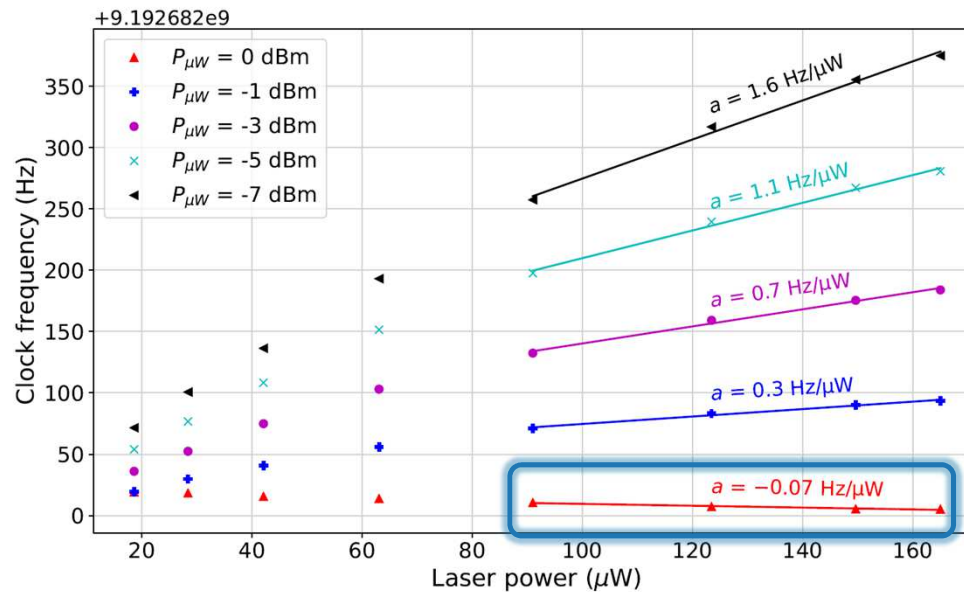
- [1]: S. Knappe *et al.*, Appl. Phys. Lett. 85, 9, 1460 (2004)  
 [2]: <https://www.microchip.com/en-us/product/CSAC-SA45S>  
 [3]: H. Zhang *et al.*, IEEE Journ. Solid State Circuits 54, 11, 3135 (2019).  
 [4]: <https://www.safran-group.com/products-services/mro-50-ruggedized-rubidium-oscillator>  
 [5]: <https://www.syrlinks.com/en/produits/all/time-frequency/mems-micro-atomic-clock-mmacc>

# Usual light-shift mitigation techniques

Light-shifts: variations of the clock frequency due to fluctuations of the laser field

- ⇒ laser power
- ⇒ laser frequency
- ⇒ microwave power

⇒ Find a microwave power setpoint that cancels the dependence of the clock frequency to laser power variations



## Drawbacks

- ⇒ Physics-package dependent
- ⇒ Does not always exist, depends on the buffer gas pressure
- ⇒ **Only immune to laser power shifts**

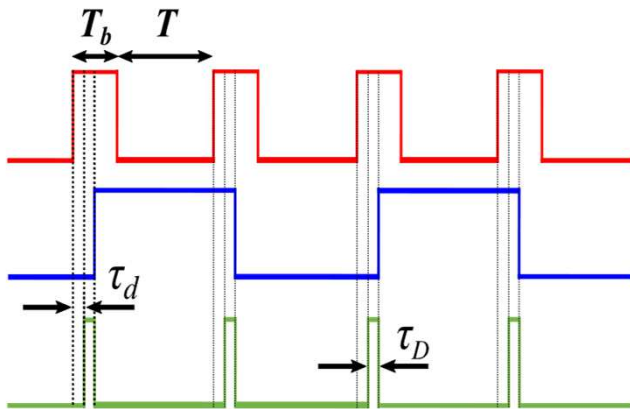


Explore pulsed Ramsey-based interrogation protocols in MEMS cells

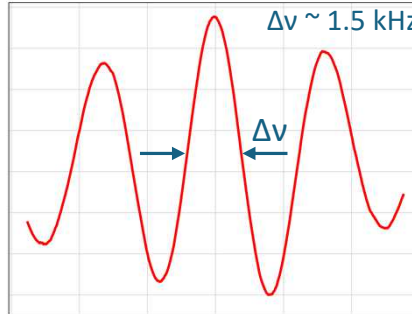
- [6] M. Zhu et al., PTTI Meeting, 311 (2000)
- [7] V. Shah et al, Appl. Phys. Lett. **89**, 151124 (2006)
- [8] R. Vicarini et al, Sens. Actua. A Phys. **280**, 99 (2018)
- [9] M. I. Vaskovskaya et al, Opt. Exp. **27**, 35, 856 (2019)
- [10] Yanagimachi et al. Appl. Phys. Lett. **116**, 101063 (2020)
- [11] Zhang et al. JOSA B **33**, 101364 (2016)

# Ramsey-CPT Interrogation in a MEMS cell

Sequence of optical CPT pulses separated by dark time  $T$  [12]



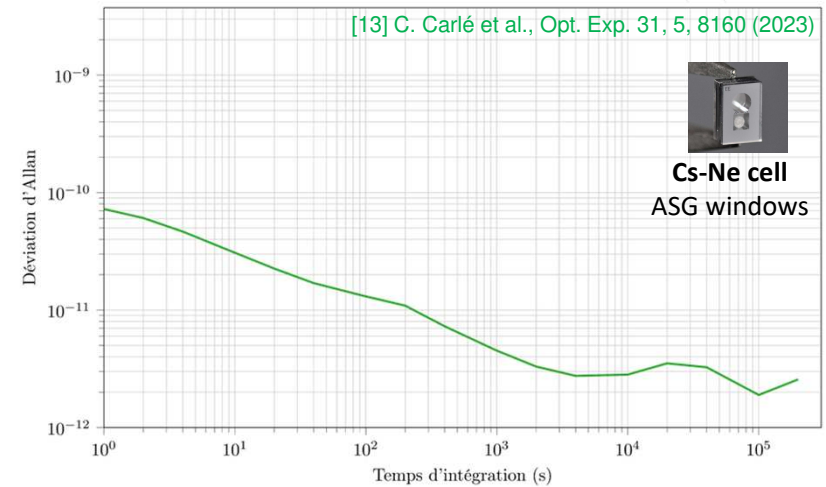
Ramsey-CPT fringes in a Cs-Ne MEMS cell



**Red:** Laser, **Blue:** LO freq., **Green:** Detection window

Typical parameters: ( $T_b = 150 \mu\text{s}$ ;  $T = 250 \mu\text{s}$ ;  $\tau_d = \tau_D = 10 \mu\text{s}$ )

EFTF-IFCS 2023, Toyama, Japan  
Stability level:  $2 \times 10^{-12}$  at 1 day (SABR-CPT)



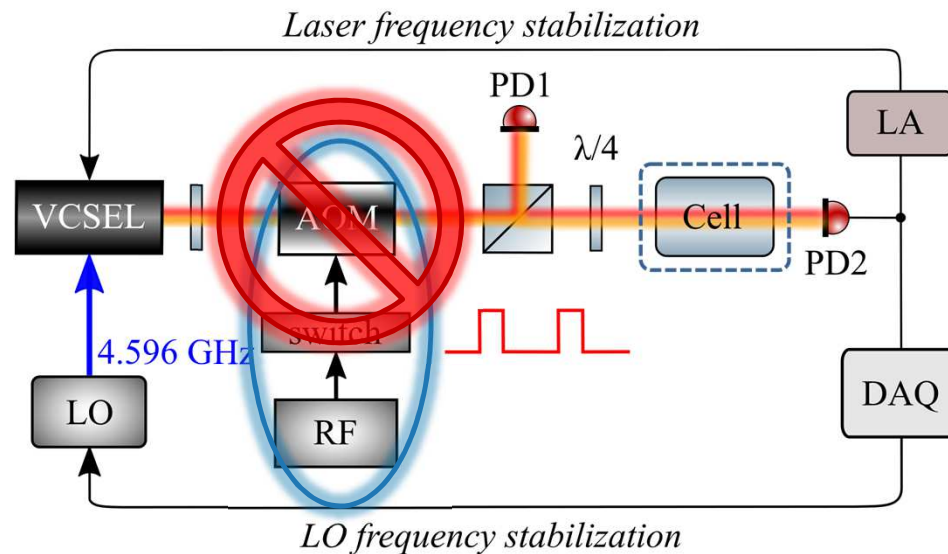
Use of Symmetric Auto-Balanced Ramsey (SABR) technique

[12] C. Carlé et al. *IEEE UFFC* 68, 10, 3249–3256 (2021)

# Ramsey-CPT Interrogation in a MEMS cell

Ramsey-CPT clock operation was demonstrated in microcells, but using an AOM

**AOM: Not compatible with a fully-miniaturized atomic clock**



**Objective: Demonstrate a Ramsey-based microcell CPT clock, without AOM**

[12] C. Carlé et al. IEEE UFFC 68, 10, 3249–3256 (2021)  
[14] M. Abdel Hafiz et al., Appl. Phys. Lett. 120, 064101 (2022)  
[13] C. Carlé et al., Opt. Exp. 31, 5, 8160 (2023)

# Two-step pulse Ramsey-CPT sequence

Possible methods to eliminate the AOM:

## 1) Microwave power modulation [15]:

- Residual carrier light persists during free evolution dark time  $T$ .

## 2) VCSEL DC current modulation

- + Laser can be completely turned off during dark time  $T$ .
- + Better conditions for Ramsey-CPT excitation.
- Laser wavelength changes due to sudden temperature variations of the VCSEL (induced by the DC current change).
- Longer time to reach the target laser wavelength for observation.

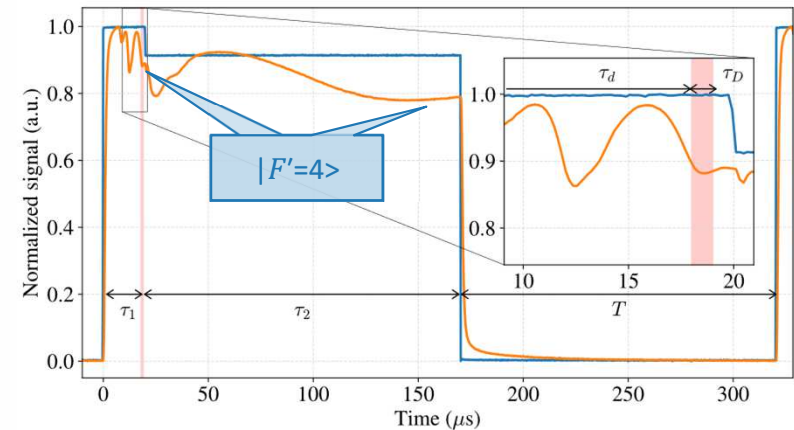
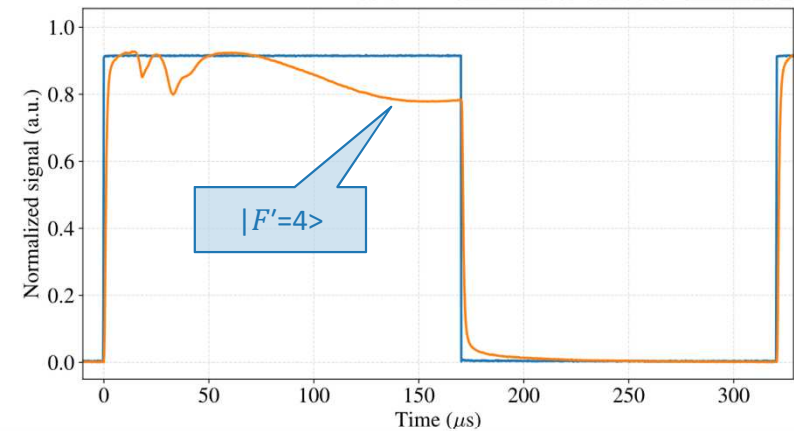


**Solution: Two-step pulse sequence [16].**

Previously demonstrated in a cm-scale glass-blown cell. No closed-loop clock operation.

**Challenge in a microcell:**

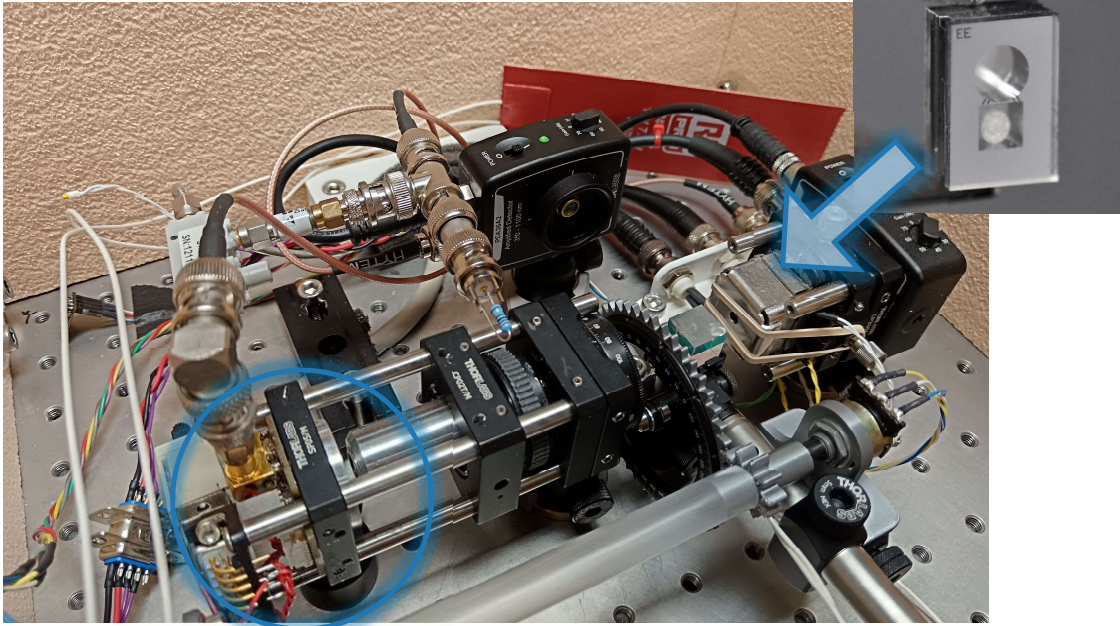
**Shorter time sequences, shorter observation times.**



[15] J. Yang *et al.*, J. Appl. Phys. 115, 093109 (2014).  
[16] T. Ide *et al.*, IEEE IFCS, pp. 167–170 (2015)

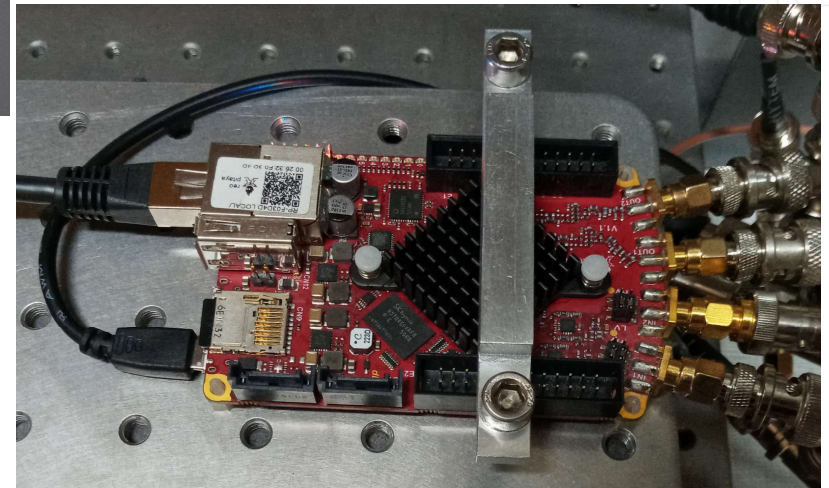
# Experimental setup

## Physics package (proof-of-concept demonstration)



### Components:

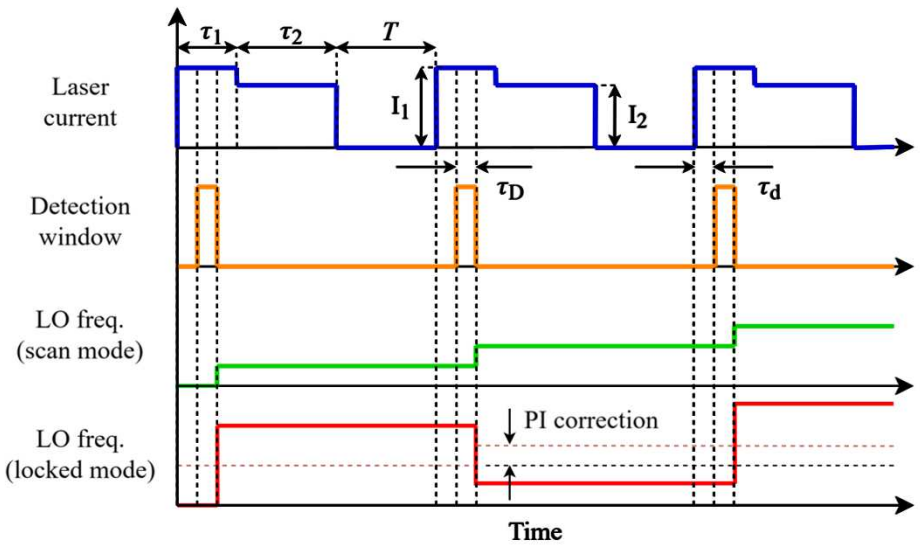
- VCSEL D1 line 895 nm
- Microcell Cs-Ne (~65 Torr)
- 14 bits Red Pitaya (STEMlab 125-14)
- Commercial microwave synthesizer
- External lock-in amplifier for laser frequency lock



### Specifications:

- Processor: Dual Core ARM Cortex A9
- FPGA: Xilinx Zynq 7010 SOC
- Sample rate: 125 MS/s (8 ns per sample)
- ADC and DAC resolution: 14 bits

# Sequence





# Software implementation



SignalGen - by: Carlos RIVERA

**Sequence generation**

Peak-Peak: 1.89V | 13759 a.u.  
Mean value: 430.91mV | 3055 a.u.  
Noise level: 774.67mV | 5628 a.u.

Disable

**Window view**

Disable

**Sequence parameters**

Enable experiment control

Presets: Ramsey\_T\_150 Save Load

| Parameter                  | Value |
|----------------------------|-------|
| <b>General</b>             |       |
| <b>ADC/DAC settings</b>    |       |
| <b>Sequence monitoring</b> |       |
| <b>Raman detuning</b>      |       |
| Contrast (%)               | 0 %   |
| <b>Long dark time (TL)</b> |       |
| <b>Region 1</b>            |       |
| Relative to                | A     |
| Window start (s)           | 18 µs |
| Window span (samples)      | 125   |
| Window End (s)             | 19 µs |
| <b>Region 2</b>            |       |
| Relative to                | H     |
| Window start (s)           | 18 µs |
| Window span (samples)      | 125   |
| Window End (s)             | 19 µs |

Points:

| Name | X (Seconds) | Y (Volts) | Comments |
|------|-------------|-----------|----------|
| 1 A  | 0.000       | 1.894     |          |
| 2 C  | 19.992u     | 1.894     |          |
| 3 D  | 20.160u     | 1.723     |          |
| 4 E  | 170.184u    | 1.723     |          |
| 5 F  | 170.352u    | 0.000     |          |
| 6 G  | 320.376u    | 0.000     |          |

Segments:

| Name     | Transition | Duration (s) | V. Offset (V) | Swing (V) | Comments |
|----------|------------|--------------|---------------|-----------|----------|
| 1 A to C | Linear     | 19.992u      | 1.894         | 0.000     |          |
| 2 D to E | Linear     | 150.024u     | 1.723         | 0.000     |          |
| 3 F to G | Linear     | 150.024u     | 0.000         | 0.000     | T 1      |
| 4 H to I | Linear     | 19.992u      | 1.894         | 0.000     |          |
| 5 J to K | Linear     | 150.024u     | 1.723         | 0.000     |          |
| 6 L to B | Linear     | 150.024u     | 0.000         | 0.000     | T 2      |

**Sequence detuning**

Peak-Peak: 25.56mV | 186 a.u.  
Mean value: 22.09µV | -75 a.u.  
Noise level: 6.96mV | 51 a.u.

Disable

- Set system parameters
- Realtime data acquisition
- Compatible with:
  - CW-CPT/Ramsey-CPT
  - SABR-CPT

▼ Region 4

Relative to K

Window start (s) 18 µs

Window span (samples) 125

Window End (s) 19 µs

▼ Synthesizer sequence

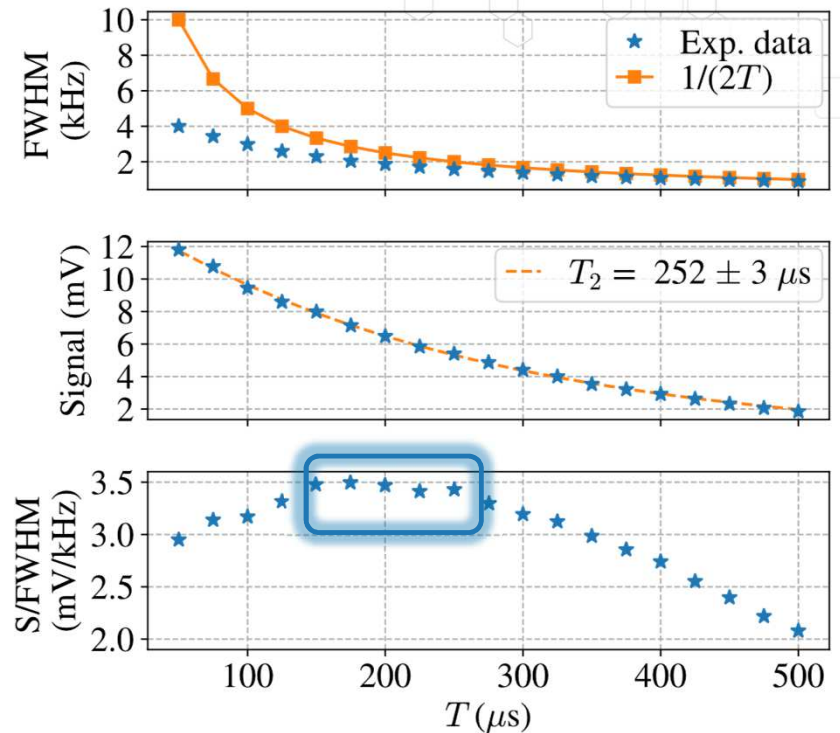
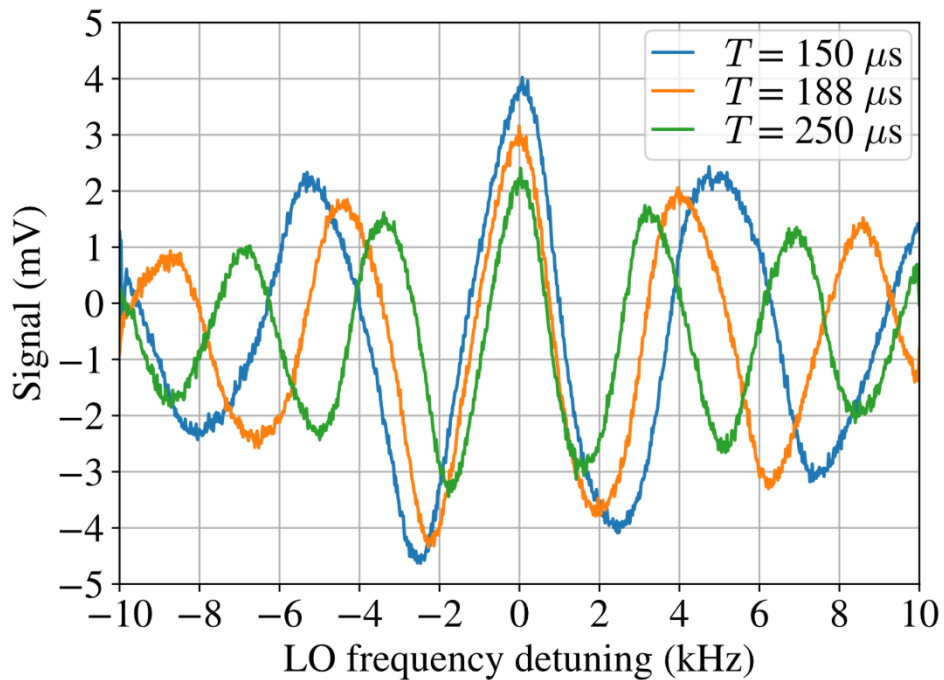
Show sequence ✓

Sequence type CW-CPT/Ramsey-CPT

Modulation depth (Hz) SABR

Frequency jump duration (s) 60 µs

# Ramsey-CPT fringes & spectroscopy



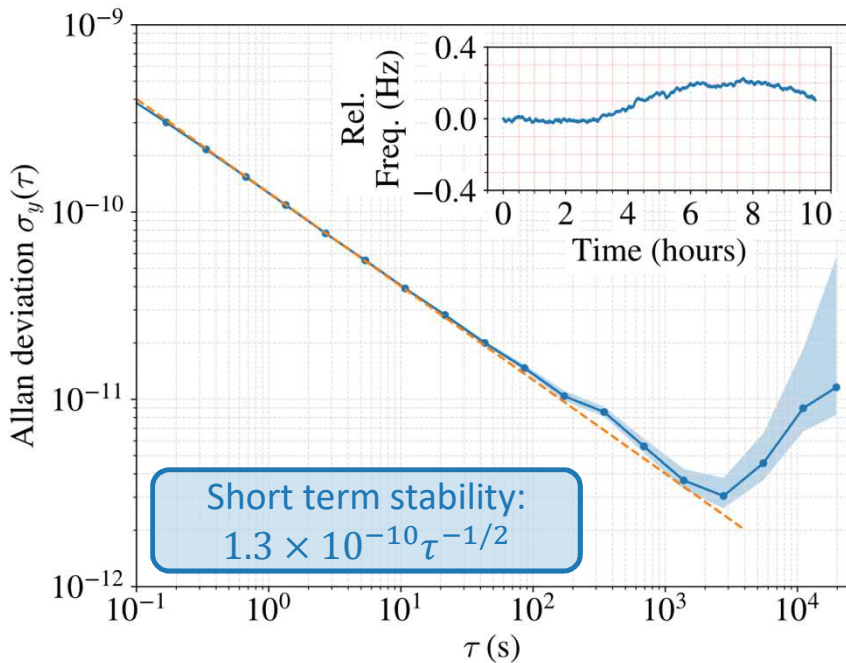
For  $T < 250 \mu\text{s}$ , the fringe width is narrower than the  $1/(2T)$  dependence.

CPT coherence lifetime  $T_2 = 252 \pm 3 \mu\text{s}$ .

Short-term stability optimized for  $T$  in the 150-250  $\mu\text{s}$  range.

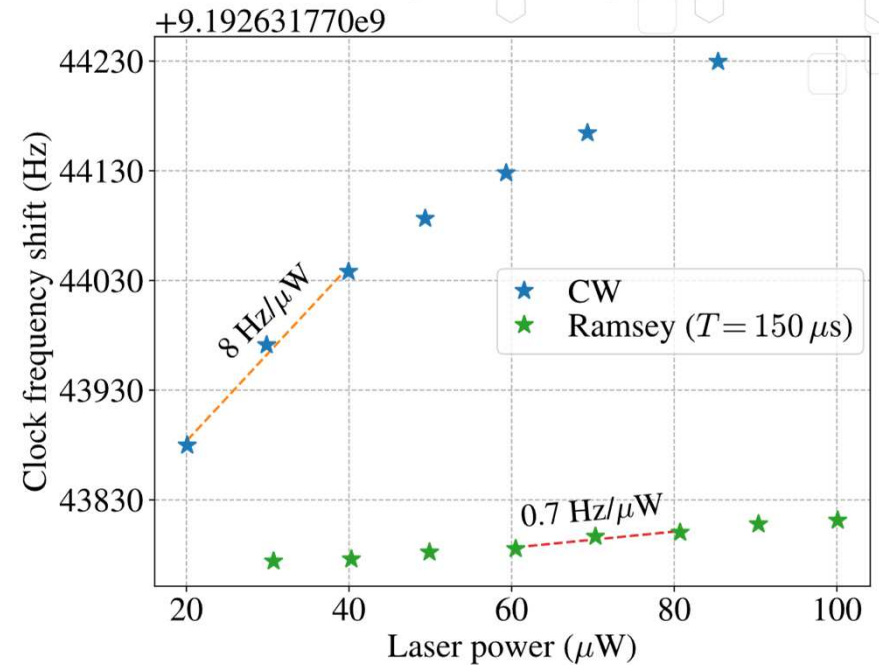
# Short-term stability and light-shift reduction

## Clock short-term stability



Stability degradation for  $\tau > 2000$  s  
residual light-shifts + Ne permeation

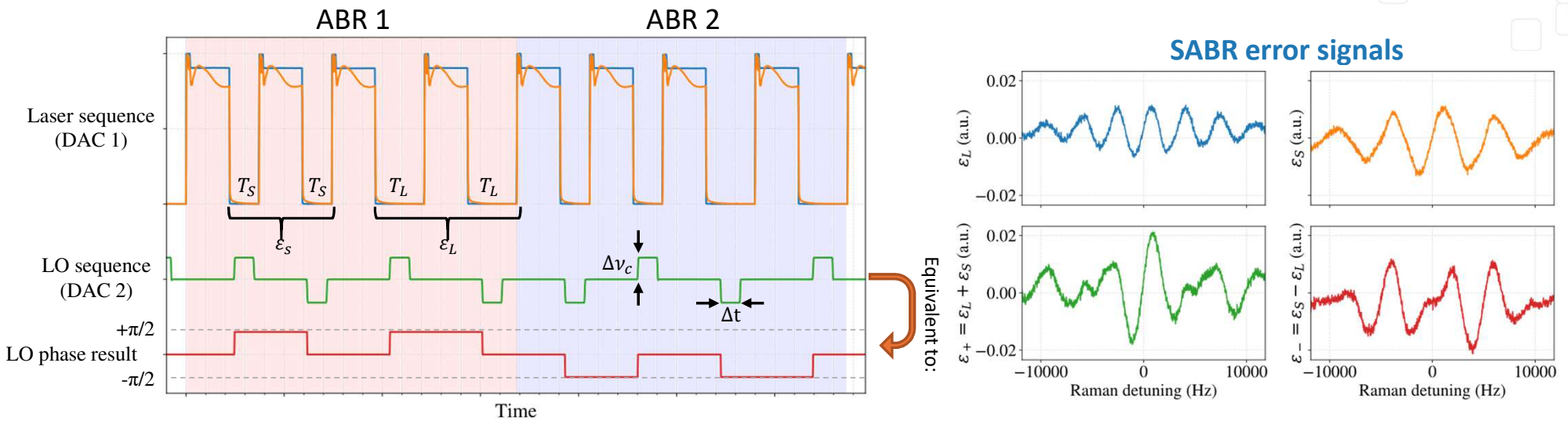
## Light-shift



Reduction of laser power sensitivity **by a factor ~10**  
in comparison with the CW regime

[17] C. M. Rivera-Aguilar *et al.*, Appl. Phys. Lett. 124, 114102 (2024)

# SABR-CPT sequence for better light-shift mitigation



$\pm\pi/2$  phase jumps are produced using frequency steps of duration  $\Delta t$ .

Sequence parameters:  $T_S = 150 \mu s$ ,  $T_L = 250 \mu s$ ,  $\Delta \nu_c = 2.08 \text{ kHz}$ ,  $\Delta t = 60 \mu s$ .

2 Ramsey-CPT cycles with short dark time ( $T_S$ )  $\rightarrow$  Error signal  $\varepsilon_S$

2 Ramsey-CPT cycles with long dark time ( $T_L$ )  $\rightarrow$  Error signal  $\varepsilon_L$

$\varepsilon + \rightarrow$  LO freq. lock.  
 $\varepsilon - \rightarrow$  Light-shift compensation.

[18] M. Abdel Hafiz *et al.*, *Appl. Phys. Lett.* (2022)  
[19] C. Carlé *et al.*, *Opt. Exp.* (2023)

# SABR-CPT implementation



**Sequence generation**

Peak-Peak: 1.91V | 13889 a.u.  
 Mean value: 396.26mV | 2804 a.u.  
 Noise level: 1.58V | 11455 a.u.

Disable

**Window view**

Disable

**Sequence parameters**

Enable experiment control

Presets: SABR\_150\_250 [Save] [Load]

| Parameter                   | Value |
|-----------------------------|-------|
| <b>Region 1</b>             |       |
| Relative to                 | A     |
| Window start (s)            | 18 µs |
| Window span (samples)       | 125   |
| Window End (s)              | 19 µs |
| <b>Region 2</b>             |       |
| Relative to                 | T     |
| Window start (s)            | 18 µs |
| Window span (samples)       | 125   |
| Window End (s)              | 19 µs |
| <b>Short dark time (TS)</b> |       |
| <b>Region 3</b>             |       |
| Relative to                 | H     |
| Window start (s)            | 18 µs |
| Window span (samples)       | 125   |
| Window End (s)              | 19 µs |

Points:

| Name | X (Seconds) | Y (Volts) | Comments |
|------|-------------|-----------|----------|
| 1 A  | 0.000       | 1.913     |          |
| 2 C  | 20.000u     | 1.913     |          |
| 3 D  | 20.400u     | 1.734     |          |
| 4 E  | 170.400u    | 1.734     |          |
| 5 F  | 170.800u    | 1.140m    |          |
| 6 G  | 320.800u    | 1.140m    |          |

Segments:

Show transition segments

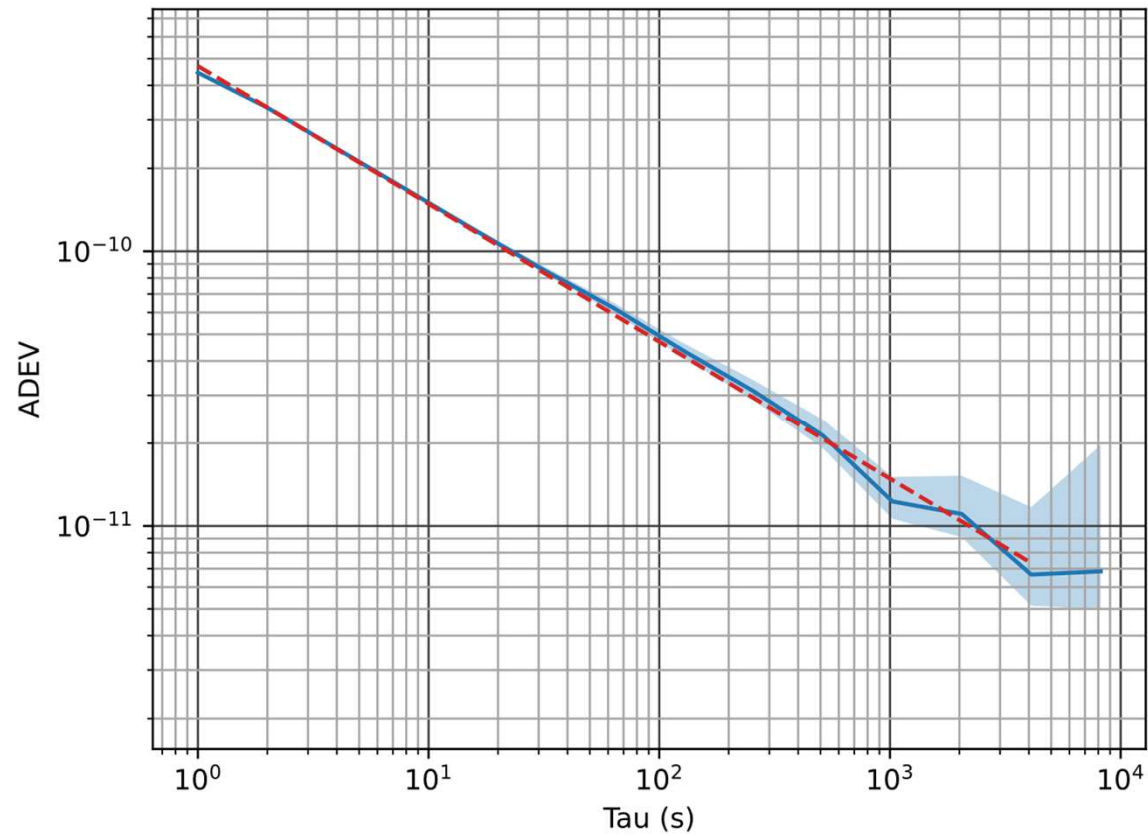
| Name     | Transition | Duration (s) | V. Offset (V) | Swing (V) | Comments |
|----------|------------|--------------|---------------|-----------|----------|
| 1 A to C | Linear     | 20.000u      | 1.913         | 0.000     |          |
| 2 D to E | Linear     | 150.000u     | 1.734         | 0.000     |          |
| 3 F to G | Linear     | 150.000u     | 1.140m        | 0.000     | TS 1     |
| 4 H to I | Linear     | 20.000u      | 1.906         | 0.000     |          |
| 5 J to K | Linear     | 150.000u     | 1.731         | 0.000     |          |
| 6 L to M | Linear     | 150.000u     | 1.140m        | 0.000     | TS 2     |

**Sequence returning**

Peak-Peak: 23.86mV | 173 a.u.  
 Mean value: -459.52µV | -78 a.u.  
 Noise level: 6.64mV | 48 a.u.

Disable

# Preliminary results of Adev with SABR



To be pursued

# Conclusions



- First demonstration of a microwave microcell atomic clock in pulsed Ramsey and SABR-CPT regimes without AOM.
- Implementation of a two-step pulse sequence in a compact setup with FPGA-based control.
- Pathway towards a fully integrated Ramsey-CPT CSACs with improved stability.

## Perspectives

Optimize the SABR interrogation technique for better light-shift mitigation.

Longer stability test with SABR-CPT and new MEMS cell with low-permeation glass windows.

