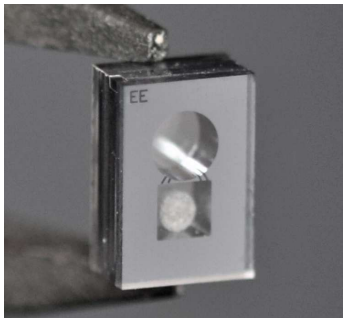
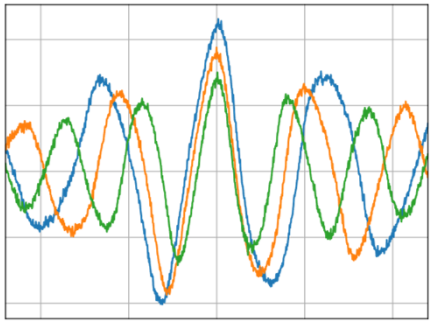
Light-shift measurements in a microcell CPT clock using symmetric autobalanced Ramsey spectroscopy





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

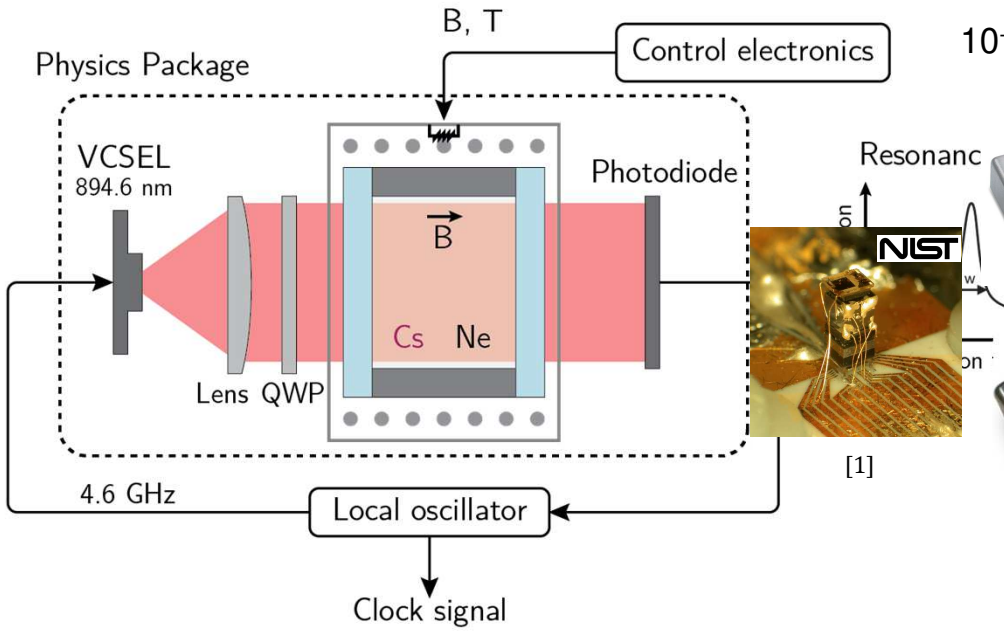
Microwave CPT-based CSACs

Typical specifications of CSACs

15-20 cm^3

100-400 mW

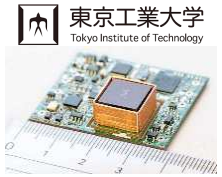
10^{-10} at 1 s, 10^{-11} at 1 day



[1]

Resonanc

[2]



[3]

[4] Not CPT

[5]

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-mmac

Usual light-shift mitigation techniques

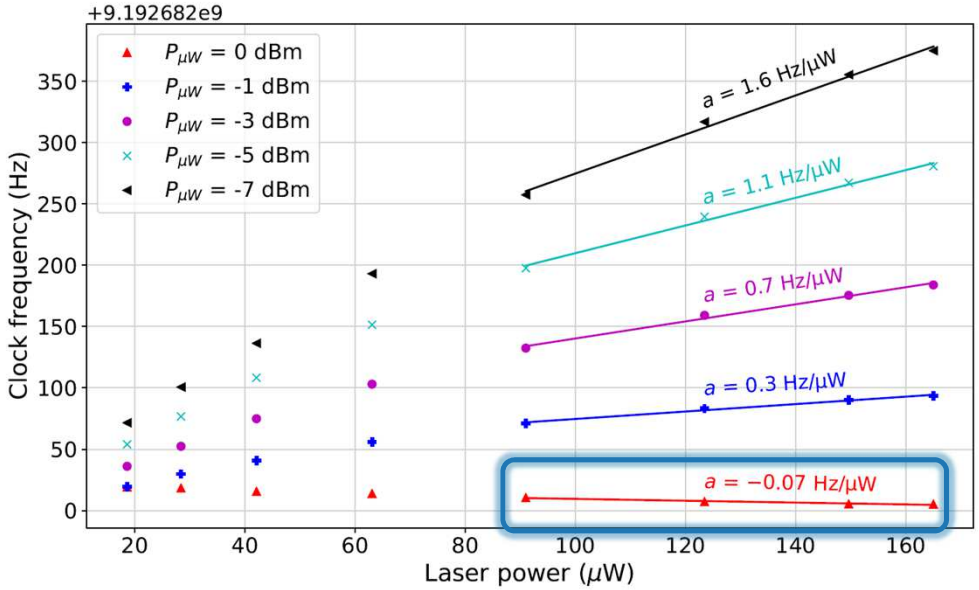
Light-shifts: variations of the clock frequency due to fluctuations of the laser field

⇒ laser power

⇒ laser frequency

⇒ microwave power

⇒ **Find a microwave power setpoint that <u>cancels the dependence</u> of the clock frequency to <u>laser power variations</u>**



Drawbacks

⇒ Physics-package dependent

⇒ Does not always exist, depends on the buffer gas pressure

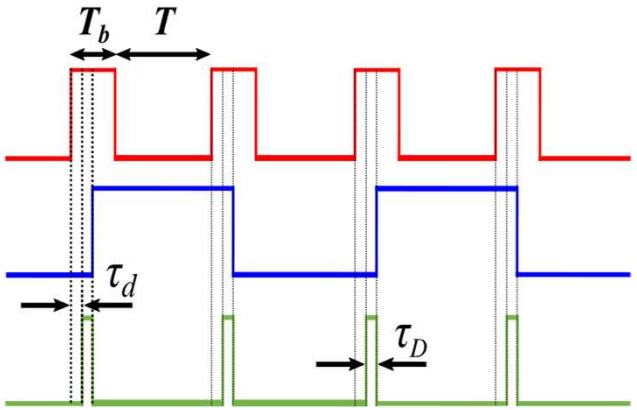
⇒ **Only immune to laser power shifts**

Explore pulsed Ramsey-based interrogation protocols in MEMS cells

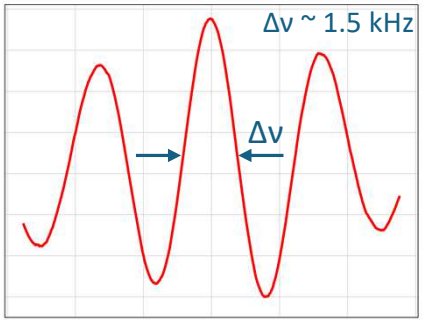
[6] M. Zhu et al., PTTI Meeting, 311 (2000)
[7] V. Shah et al, Appl. Phys. Lett. **89**, 151124 (2006)
[8] R. Vicarini et al, Sens. Actua. A Phys. **280**, 99 (2018)
[9] M. I. Vaskovskaya et al, Opt. Exp. **27**, 35, 856 (2019)
[10] Yanagimachi *et al.* Appl. Phys. Lett. **116**, 101063 (2020)
[11] Zhang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

Ramsey-CPT Interrogation in a MEMS cell

Sequence of optical CPT pulses separared by dark time *T* [12]



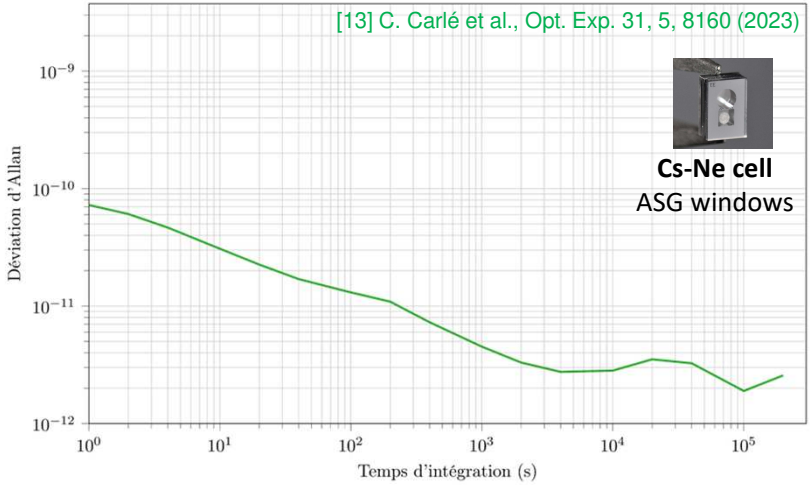
Ramsey-CPT fringes in a Cs-Ne MEMS cell



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

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

EFTF-IFCS 2023, Toyama, Japan
Stability level: 2x10^{-12} at 1 day (SABR-CPT)



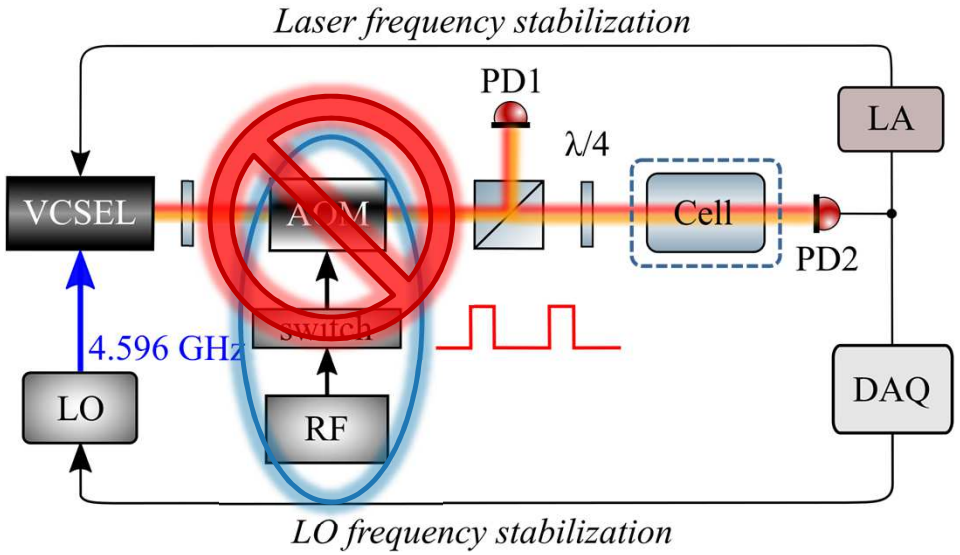
Use of Symmetric Auto-Balanced Ramsey (SABR) technique

[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.

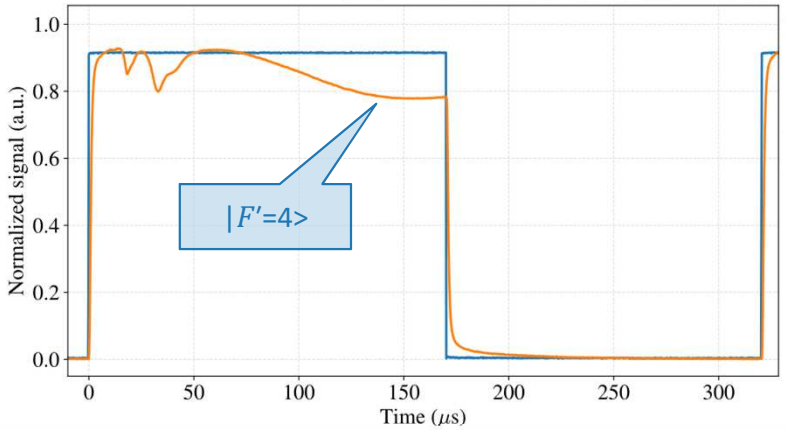
2) VCSEL DC current modulation

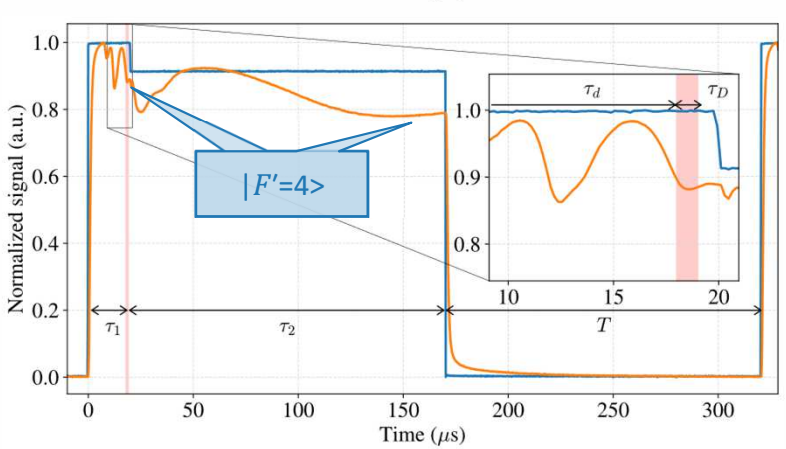
+ Laser can be completely turned off during dark time T.
+ Better conditions for Ramsey-CPT excitation.
- Laser wavelength changes due to sudden temperature variations of the VCSEL (induced by the DC current change).
- Longer time to reach the target laser wavelength for observation.

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.

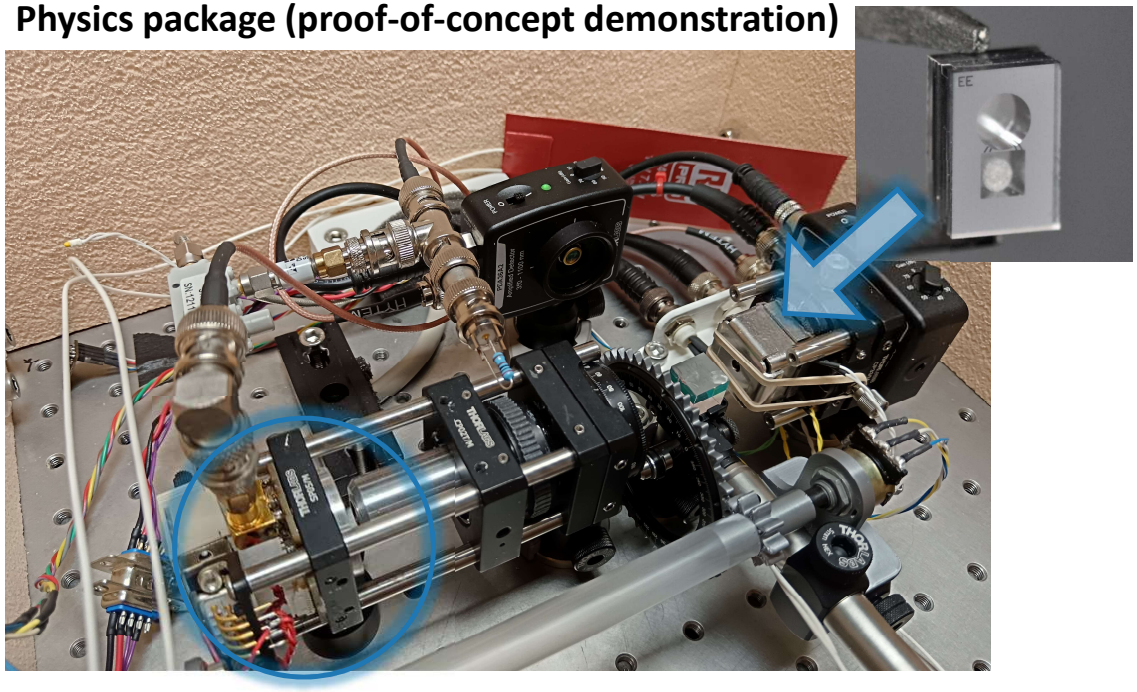




[15] J. Yang *et al.*, J. Appl. Phys. 115, 093109 (2014).
[16] T. Ide *et al.*, IEEE IFCS, pp. 167–170 (2015)

Experimental setup

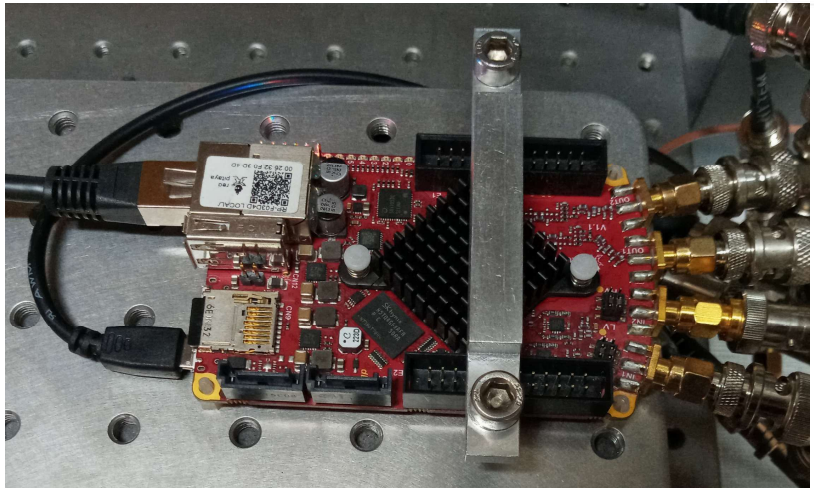
Physics package (proof-of-concept demonstration)



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

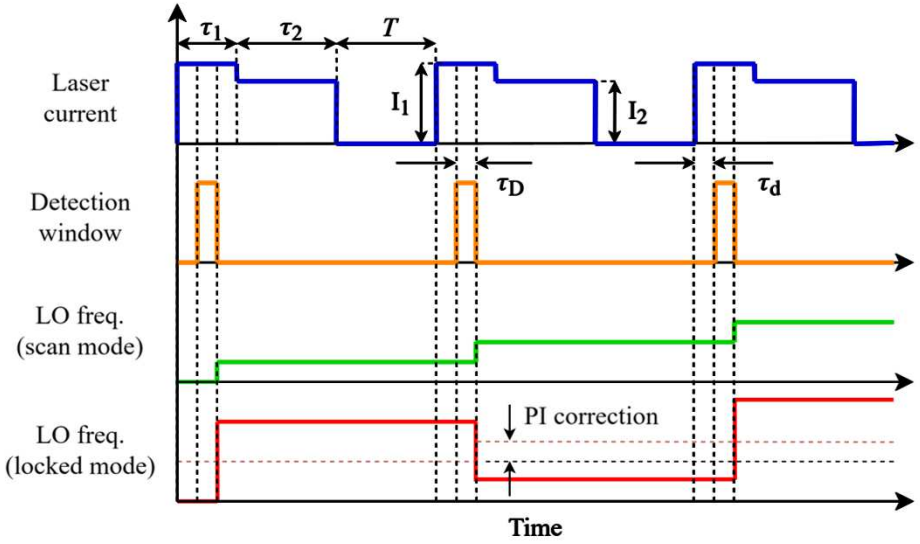
Electronics



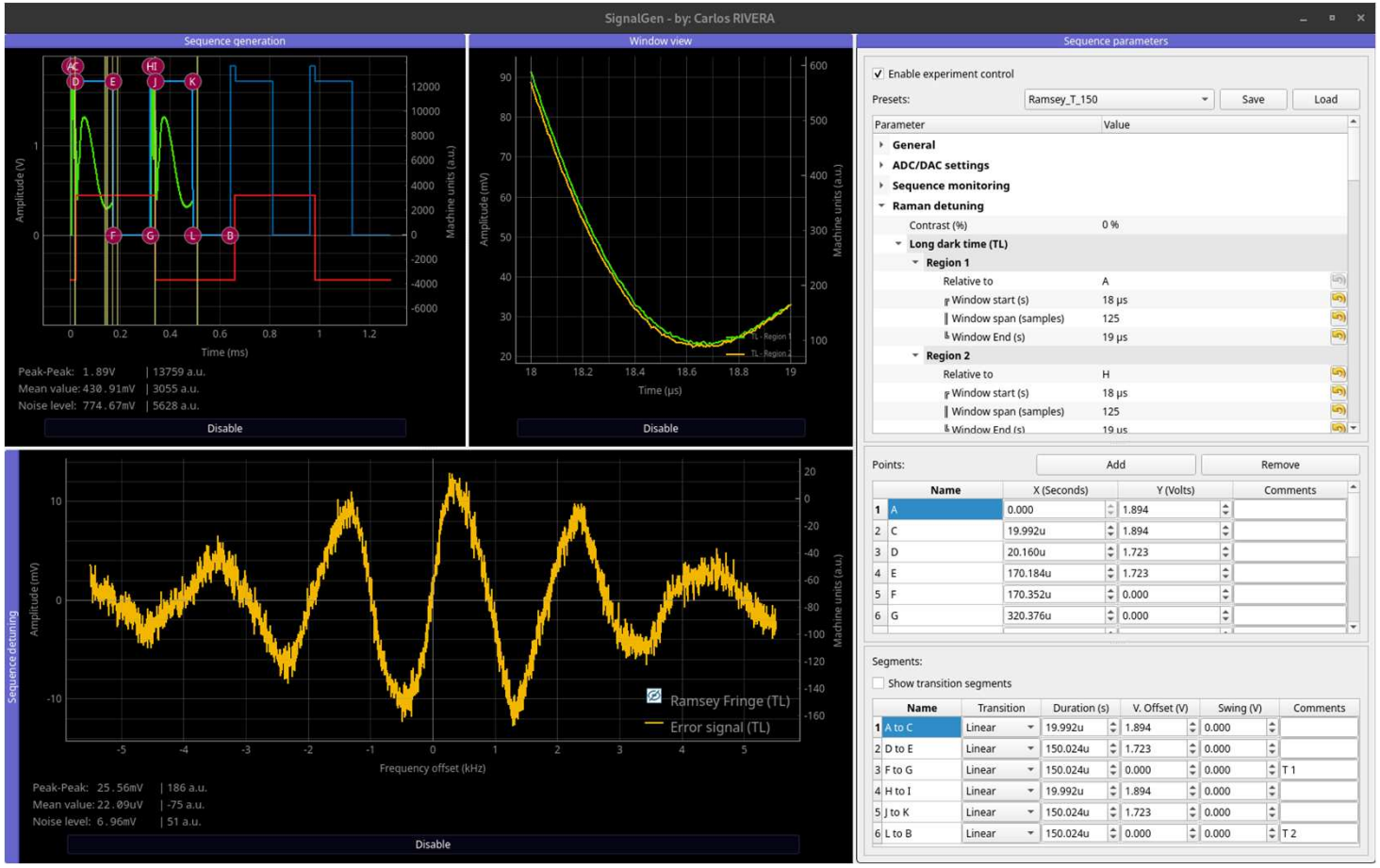
Specifications:

- 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

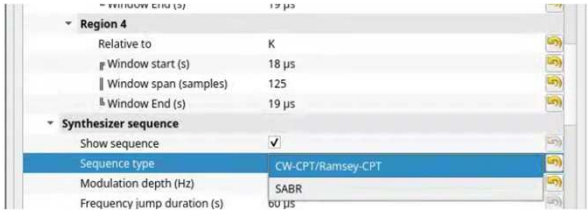
Sequence


τ_1
τ_2
T
Laser current
I_1
I_2
τ_D
τ_d
Detection window
LO freq. (scan mode)
PI correction
LO freq. (locked mode)
Time

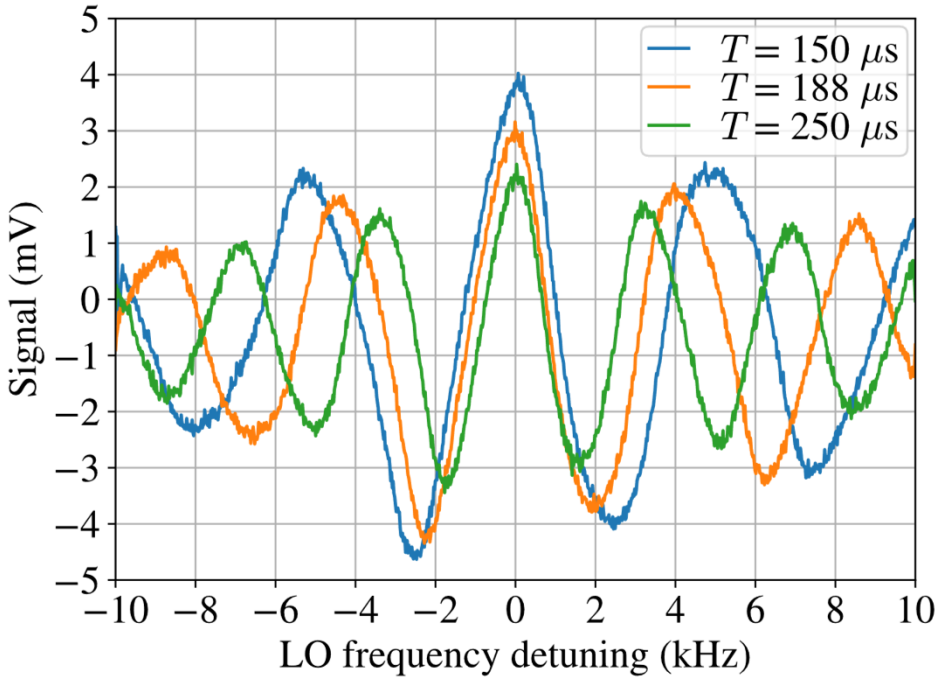
Software implementation

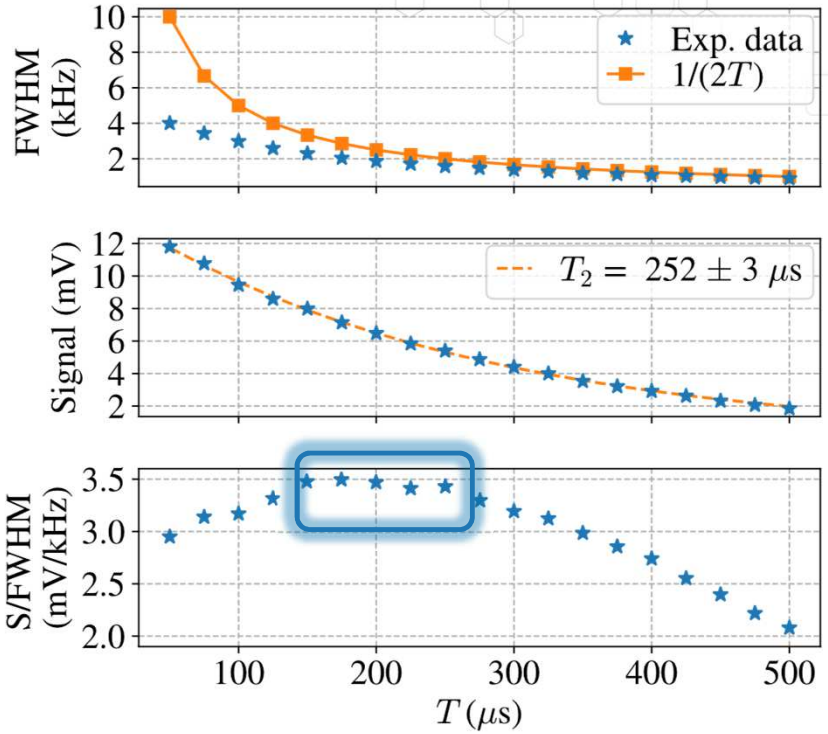


- Set system parameters
- Realtime data acquisition
- Compatible with:
  - CW-CPT/Ramsey-CPT
  - SABR-CPT



Ramsey-CPT fringes & spectroscopy



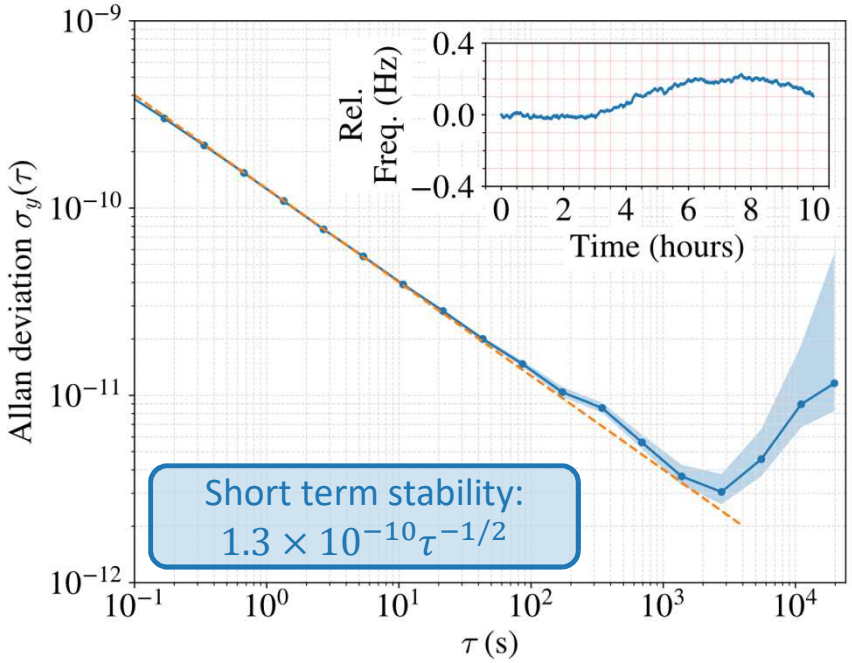


For T < 250 μs, the fringe width is narrower than the 1/(2T) dependence.
CPT coherence lifetime $T_2 = 252 \pm 3\ \mu s$.
Short-term stability optimized for T in the 150-250 μs range.

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

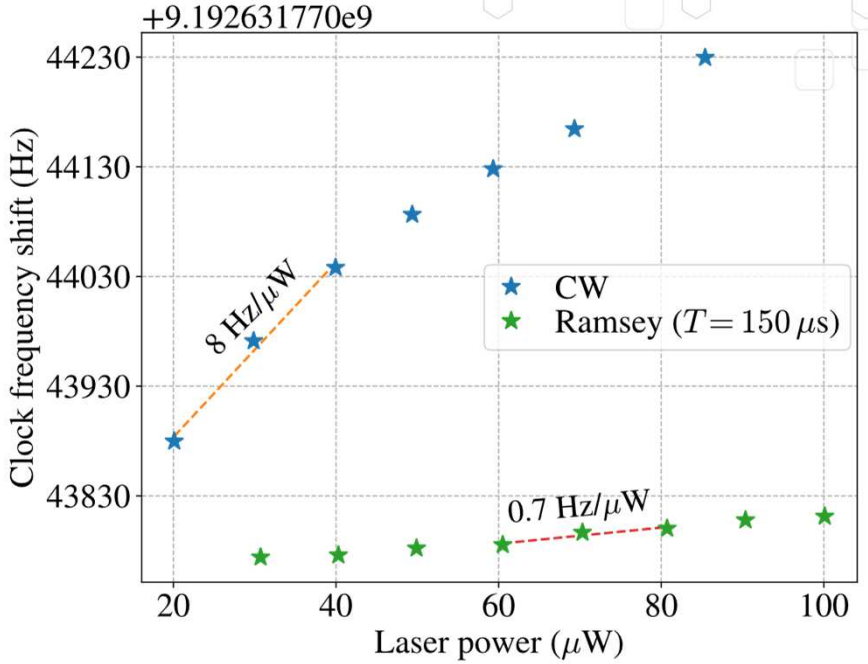
Short-term stability and light-shift reduction

Clock short-term stability



Stability degradation for τ > 2000 s
residual light-shifts + Ne permeation

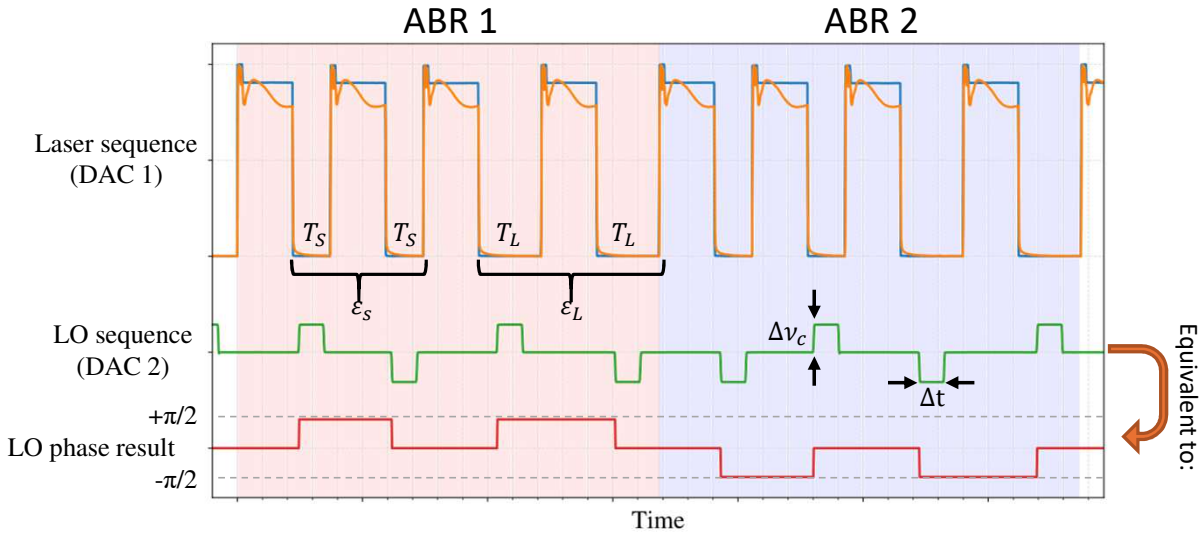
Light-shift

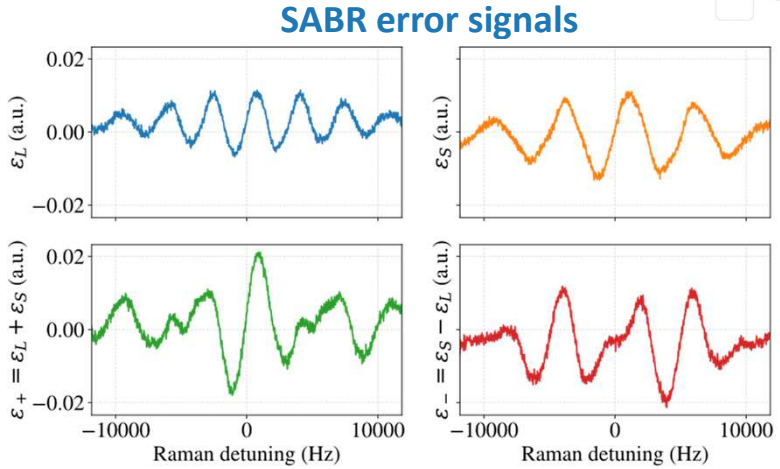


Reduction of laser power sensitivity **by a factor ~10**
in comparison with the CW regime

[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 Δt.

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

ε + → LO freq. lock.

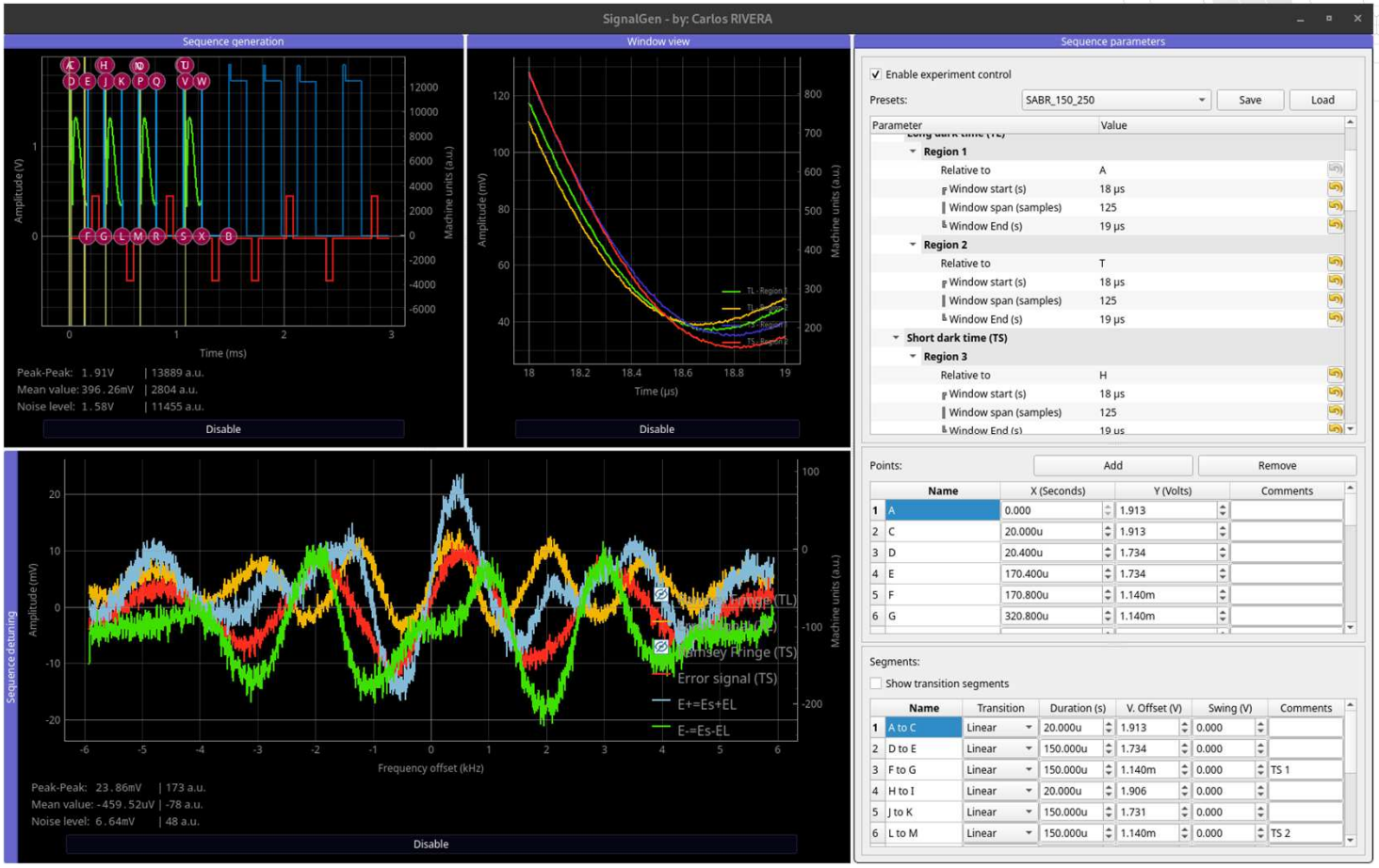
ε - → Light-shift compensation.

2 Ramsey-CPT cycles with short dark time (T_S) →Error signal ε_s

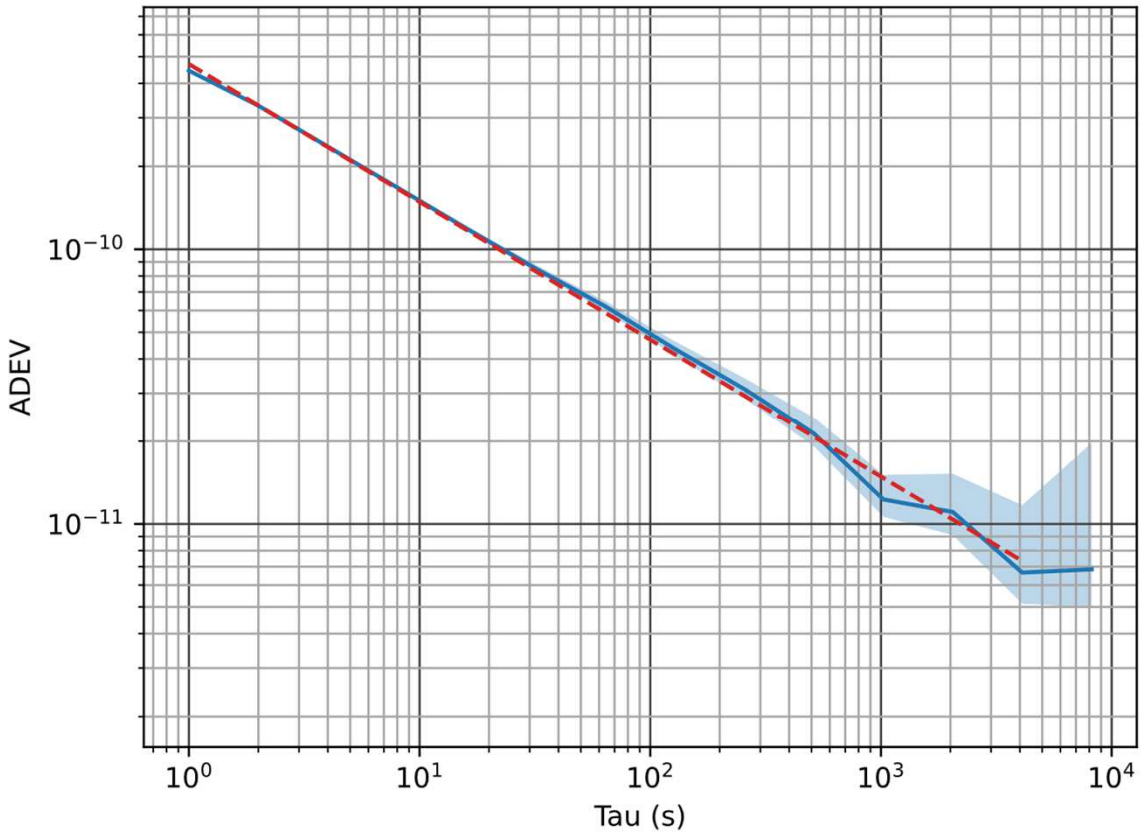
2 Ramsey-CPT cycles with long dark time (T_L) → Error signal ε_L

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

SABR-CPT implementation



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.