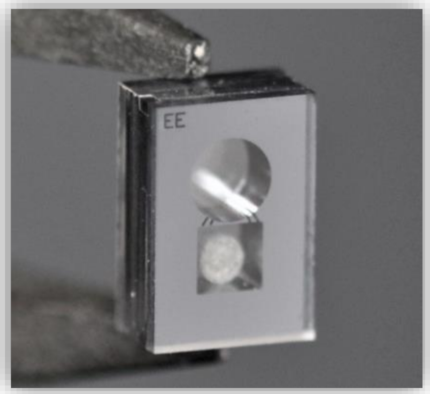
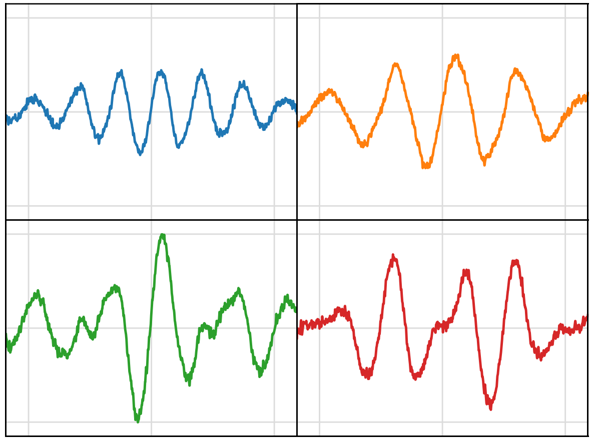
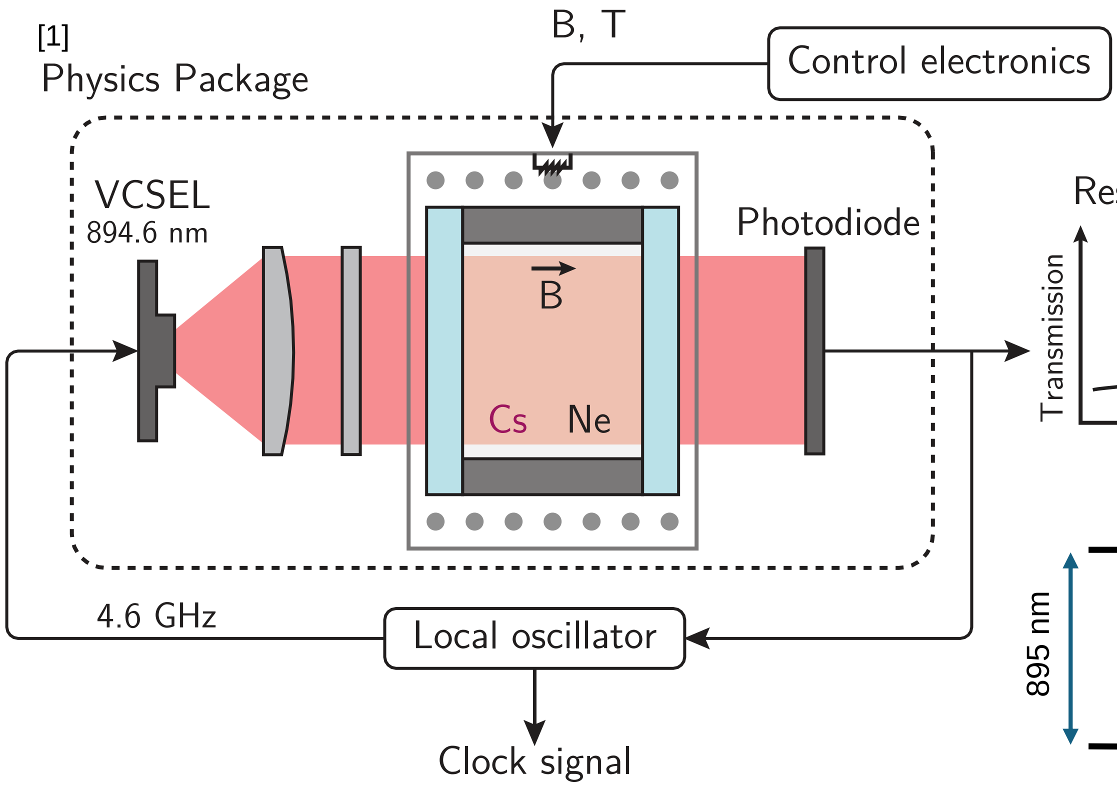
Microcell CPT atomic clock in pulsed regime with 2.5×10^{-12} frequency stability at 10^5 seconds

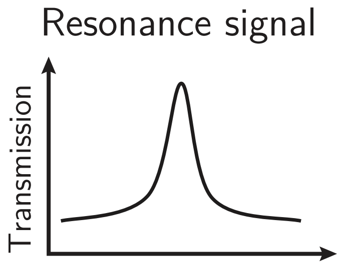


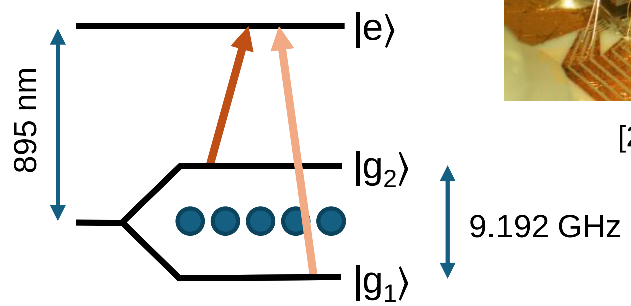


Carlos M. Rivera-Aguilar, A. Mursa, J-M. Friedt, E. Klinger, M. Abdel Hafiz, N. Passilly, and R. Boudot

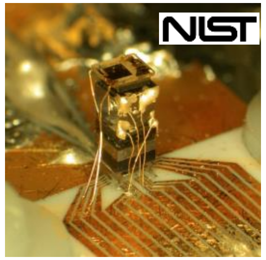
Microwave CPT-based CSACs





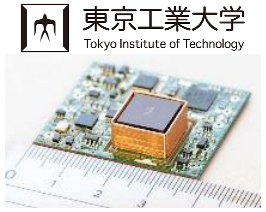


Typical specifications of CSACs
15-20 cm^3
100-400 mW
10^{-10} at 1 s, 10^{-11} at 1 day



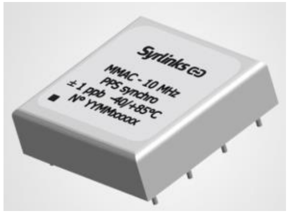
[2]

[3]



[4]

[5] Not CPT



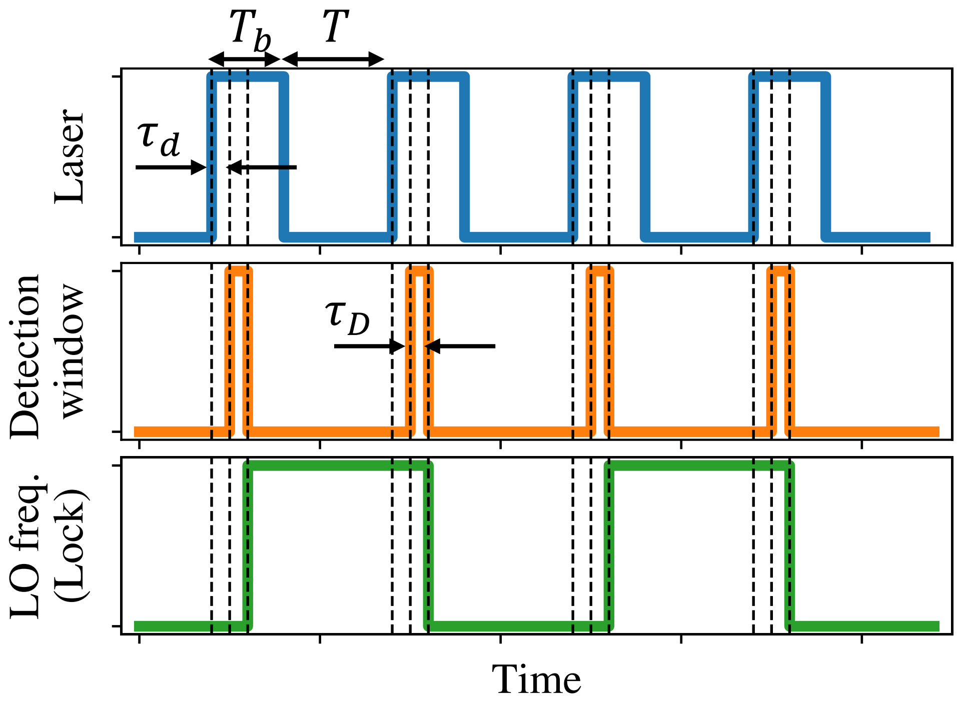
[6]

Limitations:
Short-term stability: VCSEL FM noise
Long-term stability: **Light-shifts** and collisional shifts

[1]: V. Maurice. PhD thesis, FEMTO-ST, 2016
[2]: S. Knappe *et al*., Appl. Phys. Lett. **85**, 9, 1460 (2004)
[3]: https://www.microchip.com/en-us/product/csac-sa65
[4]: H. Zhang *et al*., IEEE Journ. Solid State Circuits 54, 11, 3135 (2019).
[5]: https://www.safran-group.com/products-services/mro-50-ruggedized-rubidium-oscillator
[6]: https://www.syrlinks.com/en/produits/all/time-frequency/mems-micro-atomic-clock-mmac

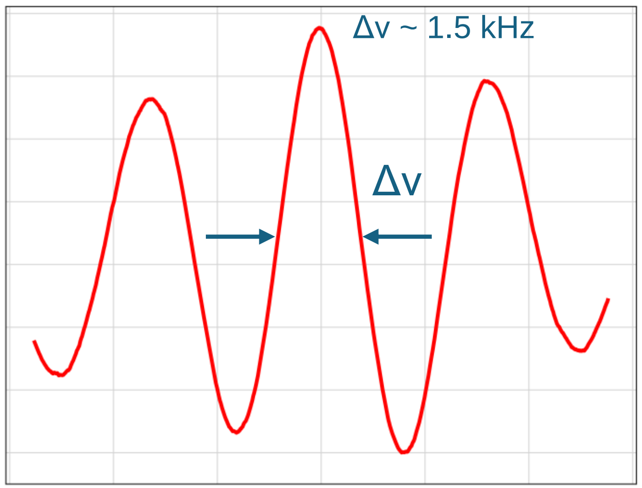
Ramsey-CPT Interrogation in a MEMS cell

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



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

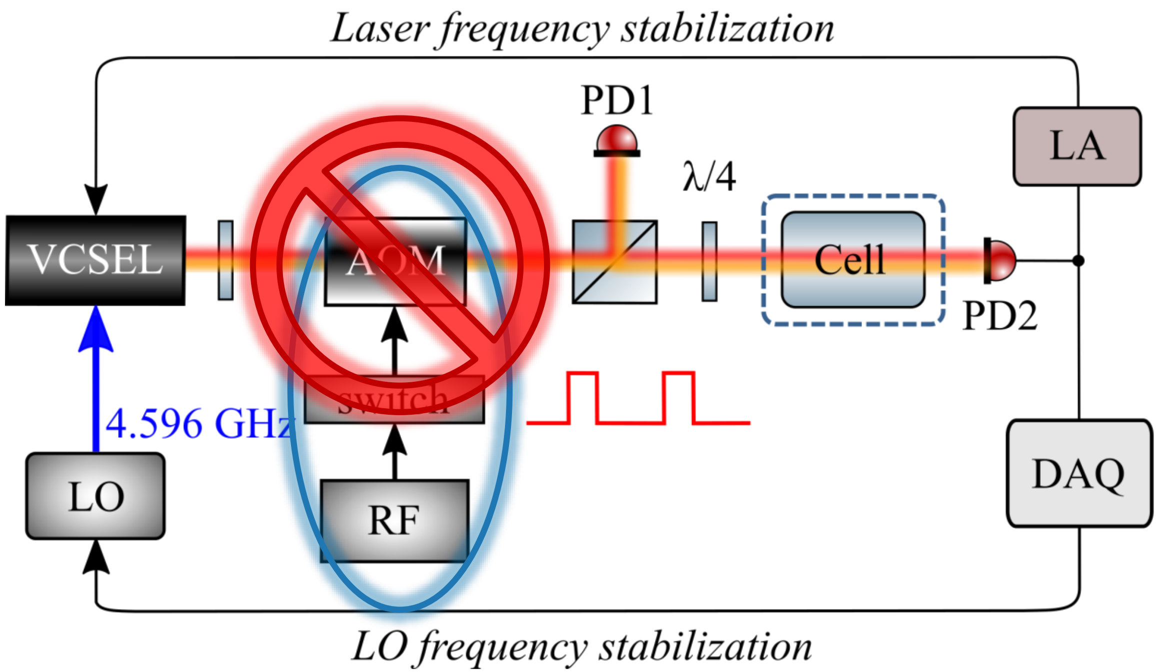
Ramsey-CPT fringes
in a Cs-Ne MEMS cell



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

[7] C. Carlé *et al.*, IEEE UFFC **68**, 10, 3249–3256 (2021)
[8] M. Abdel Hafiz *et al.*, Appl. Phys. Lett. **120**, 6, 064101 (2022)
[9] 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 [10]:

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

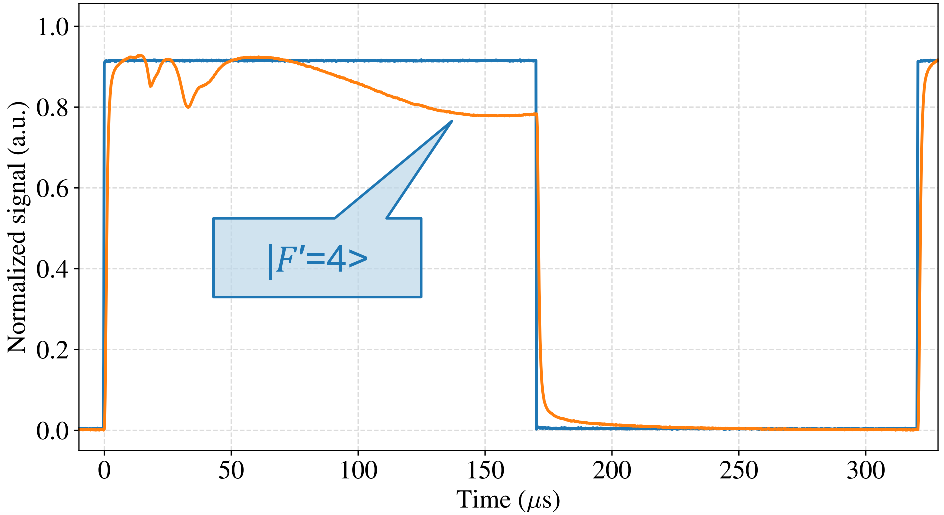
2) VCSEL DC current modulation

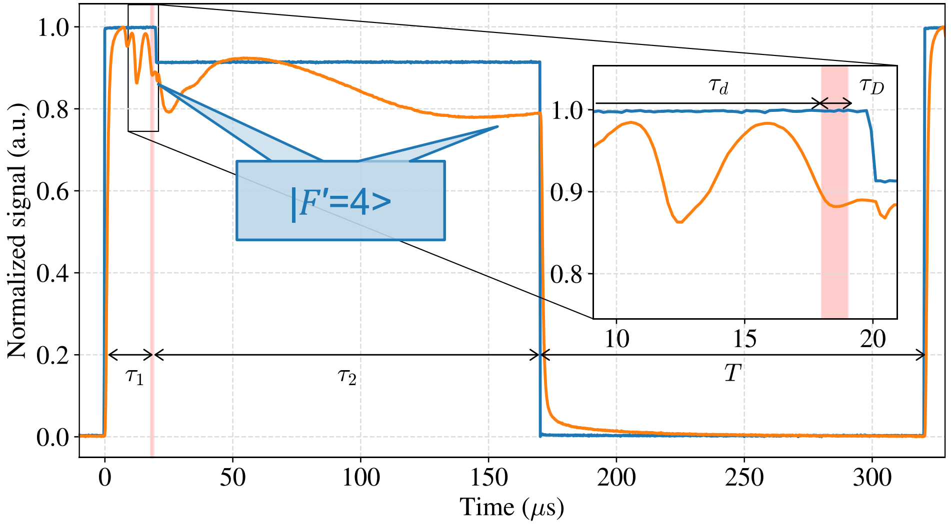
+ Laser can be completely turned off during dark time T.
+ Better conditions for Ramsey-CPT excitation.

- 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 [11].
Previously demonstrated in a cm-scale glass-blown cell. No closed-loop clock operation.

Challenge in a microcell:
Shorter time sequences, shorter observation times.

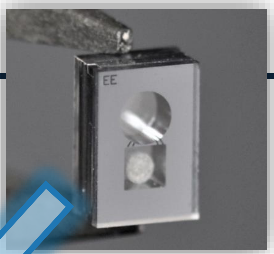


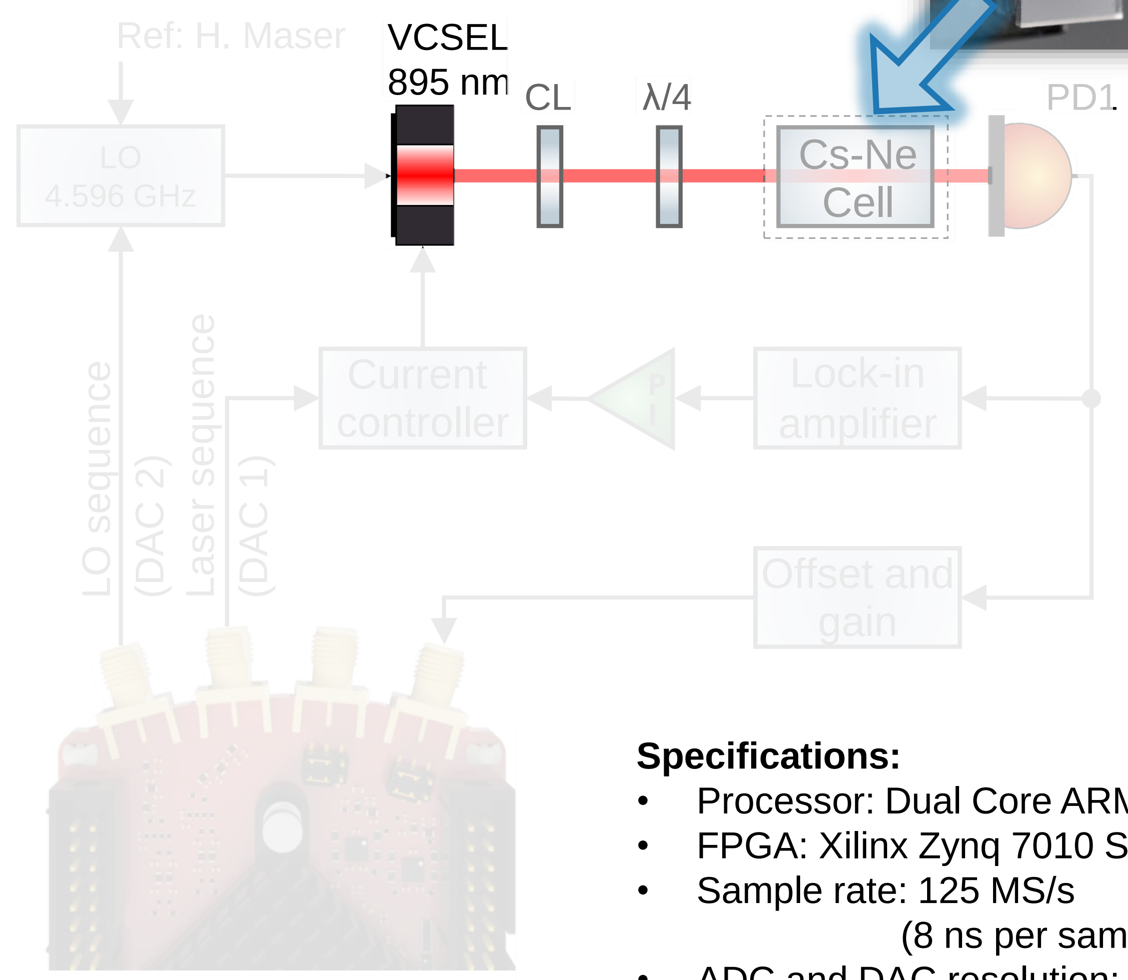


[10] J. Yang *et al.*, J. Appl. Phys. **115**, 9, 093109 (2014)
[11] T. Ide *et al.*, IEEE IFCS, pp. 167–170 (2015)

Experimental setup

Physics package (proof-of-concept demonstration)



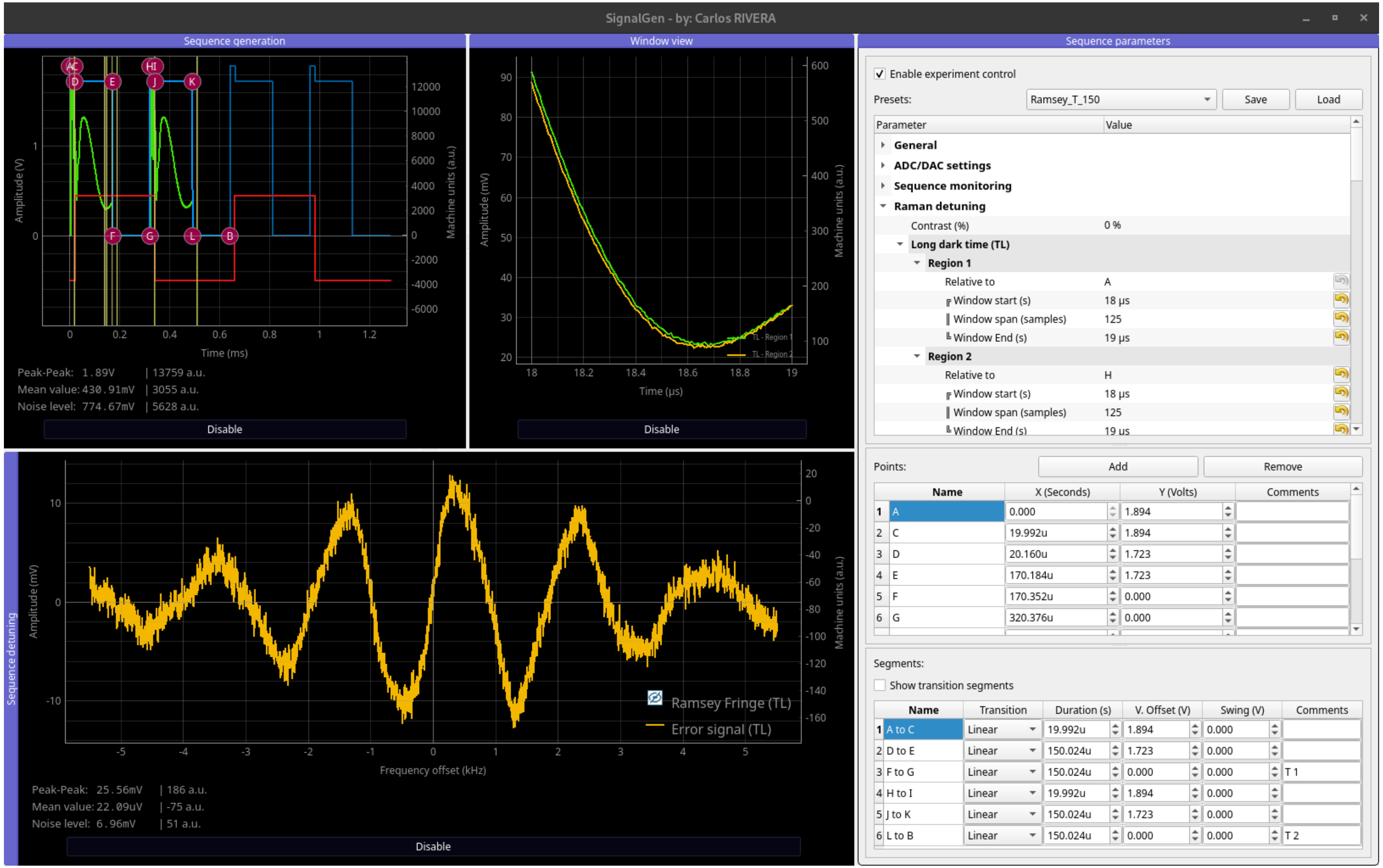


Red Pitaya (StemLab 125-14)

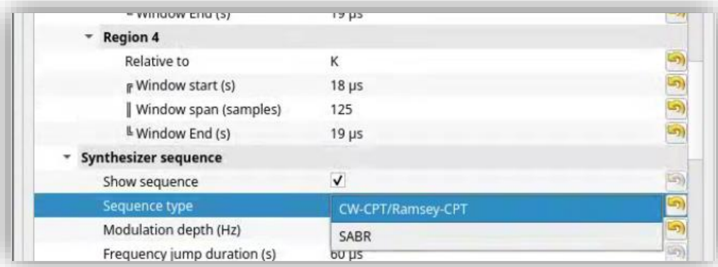
Components:
- VCSEL D1 line 895 nm
- Microcell Cs-Ne (~65 Torr)
- 14 bits Red Pitaya (STEMlab 125-14)
- Commercial microwave synthesizer
- External lock-in amplifier for laser frequency lock

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

Software implementation

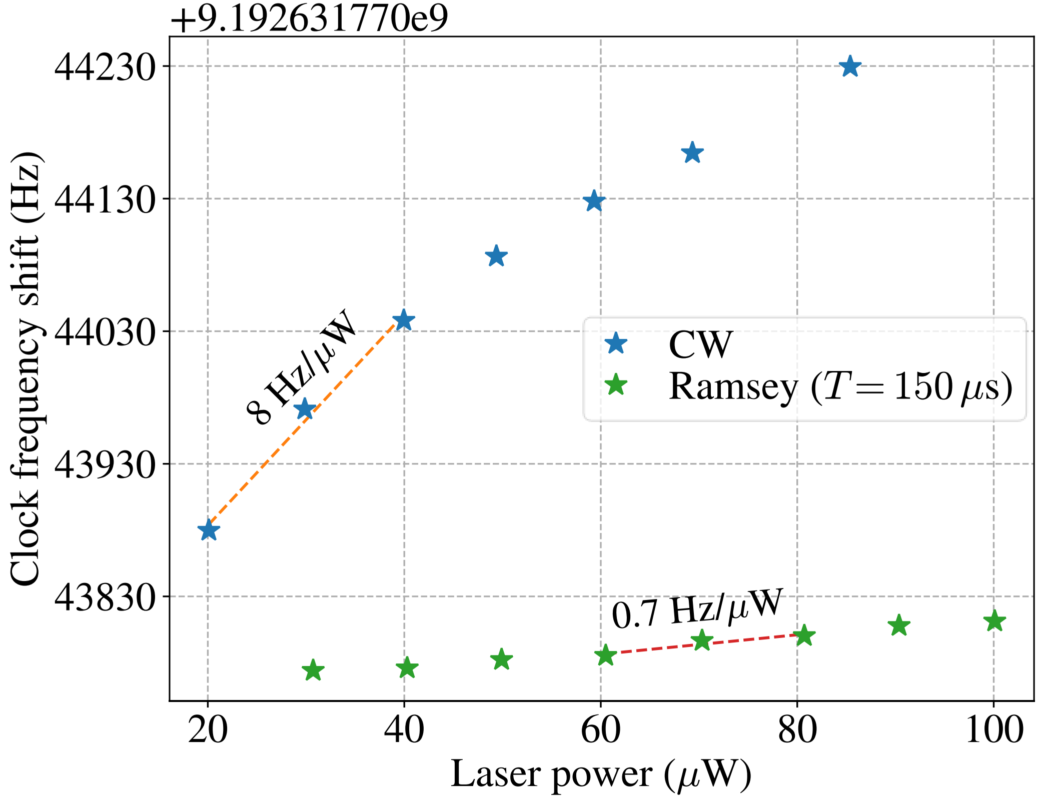


- Set system parameters
- Realtime data acquisition
- Compatible with:
  - CW-CPT/Ramsey-CPT
  - SABR-CPT



Light-shift reduction and short-term stability

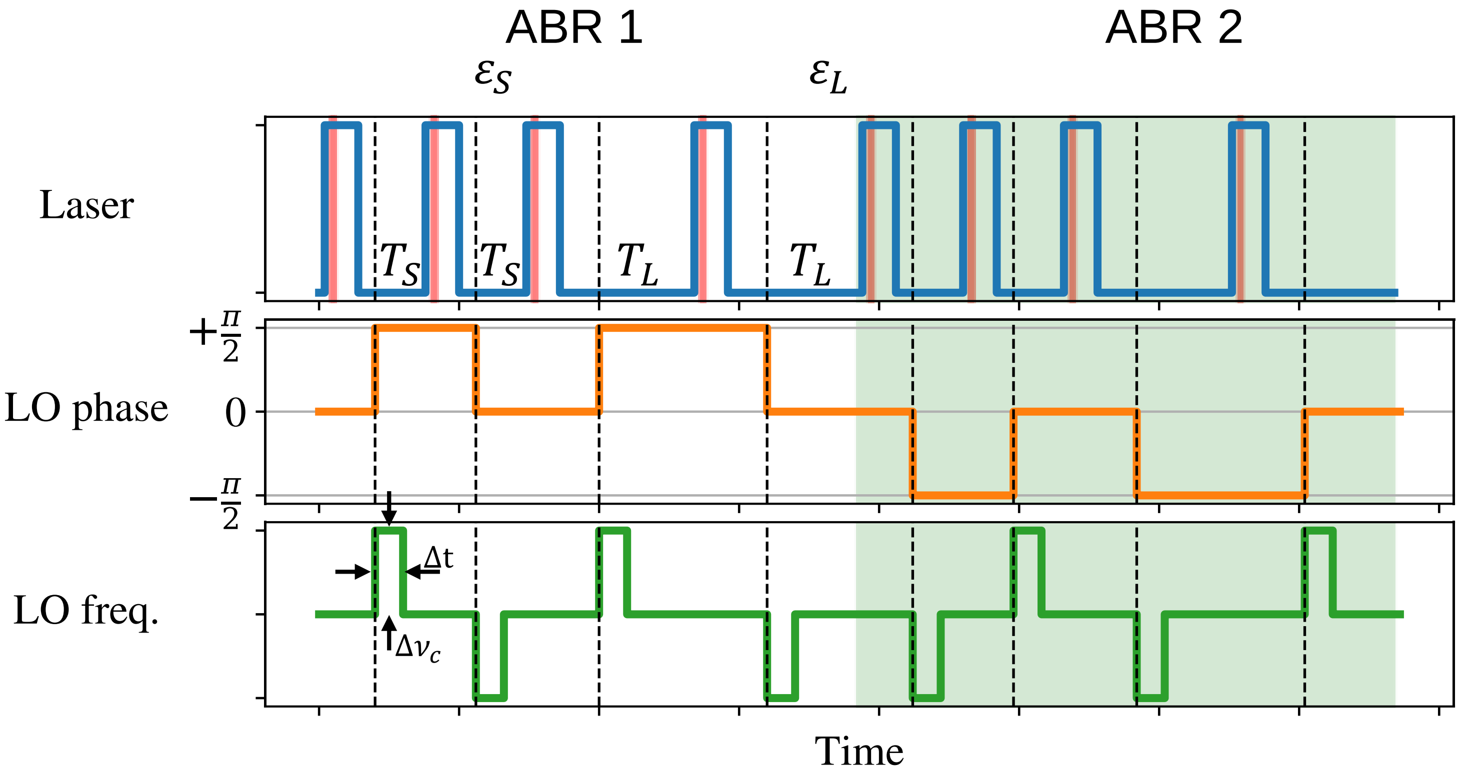
Light-shift

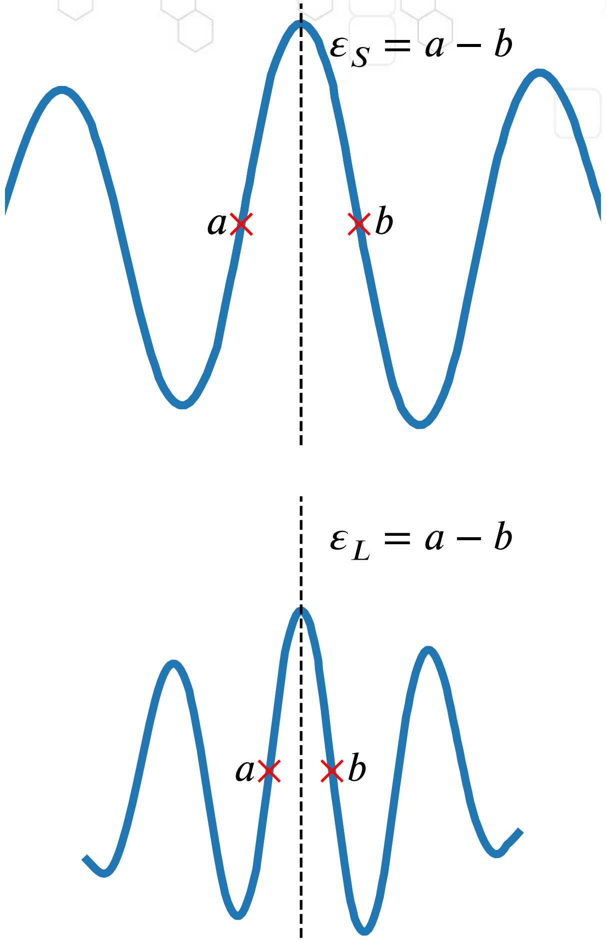


Reduction of laser power sensitivity **by a factor ~10**
in comparison with the CW regime

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

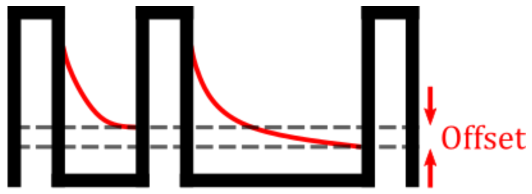
Symmetric autobalanced Ramsey (SABR)





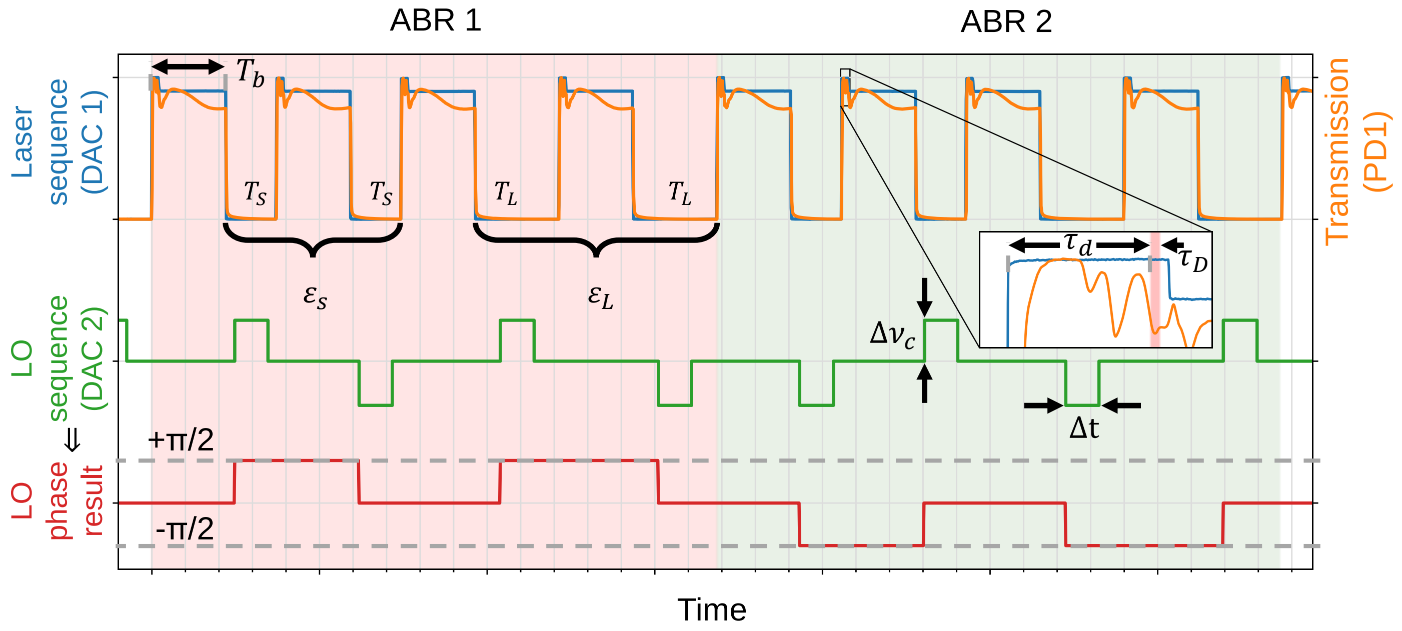
2 Ramsey-CPT cycles with **short** dark time (T_S) →Error signal ε_s
2 Ramsey-CPT cycles with **long** dark time (T_L) → Error signal ε_L

Symmetrization of the sequence

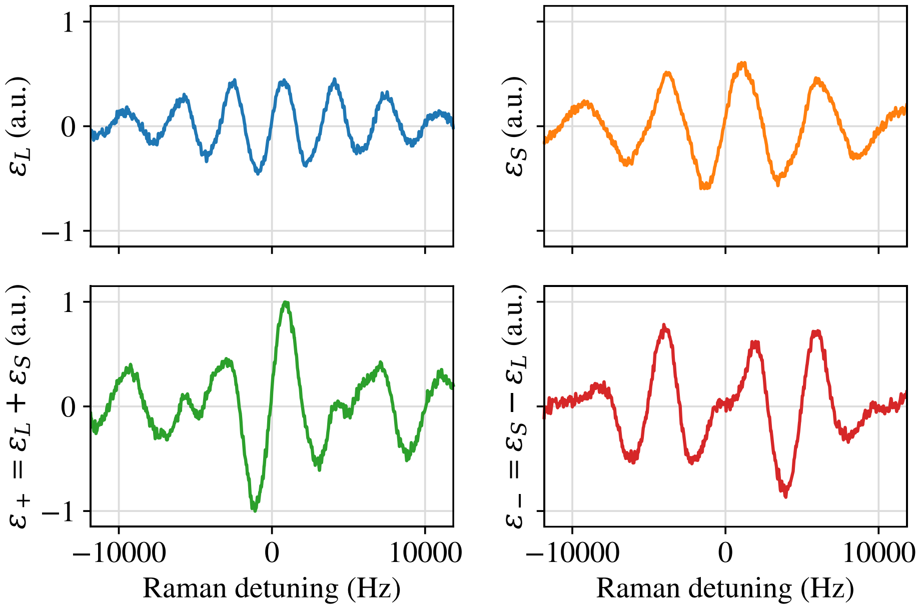


Cancels the memory effect of the atoms

SABR-CPT sequence for better light-shift mitigation



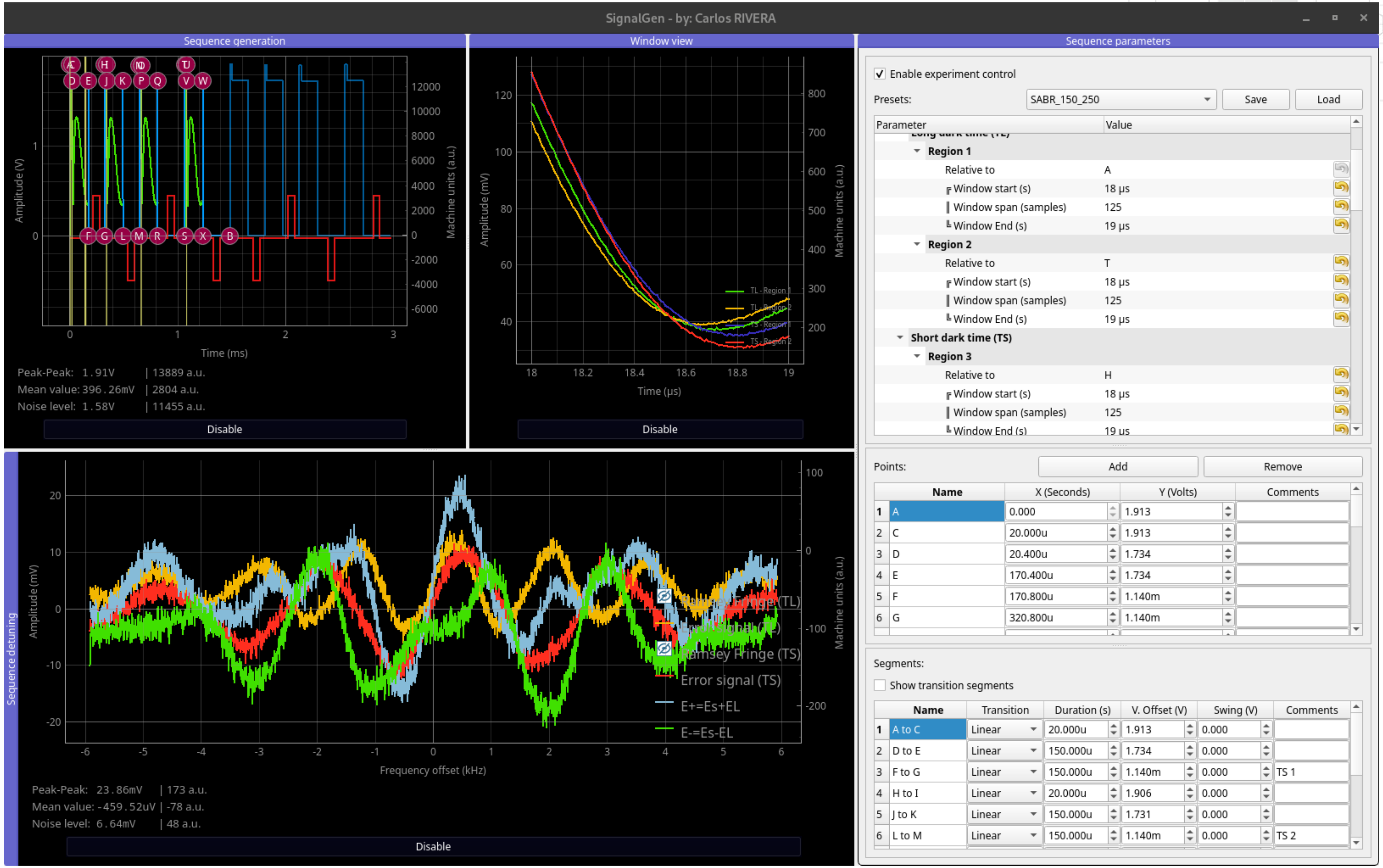
SABR error signals



$\pm\pi/2$ phase jumps are produced using frequency steps of duration Δt.
Sequence parameters: $T_S =$ 150 μs, $T_L = 250\ \mu$s, $\Delta\nu_c = 2.08$ kHz, $\Delta t = 60\ \mu$s.

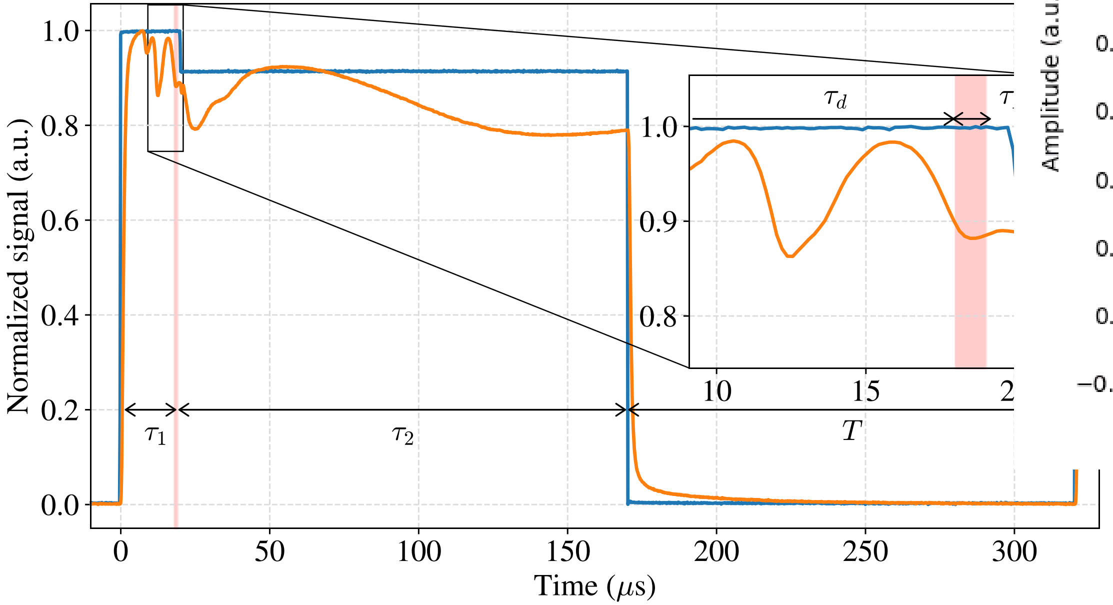
$\varepsilon_+ \rightarrow$ LO freq. lock.
$\varepsilon_- \rightarrow$ Light-shift compensation.

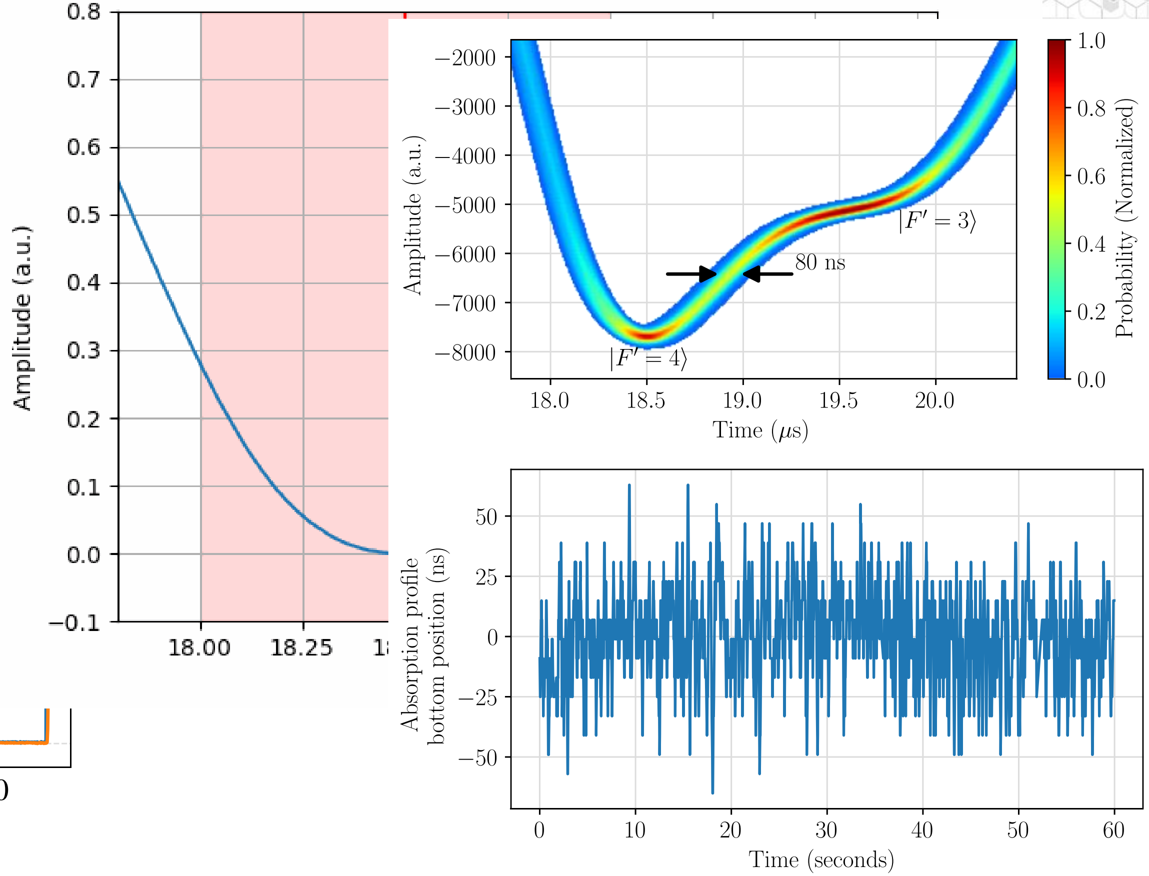
SABR-CPT implementation



Observation timing effects

Fluctuations were observed in the absorption profile within the observation window



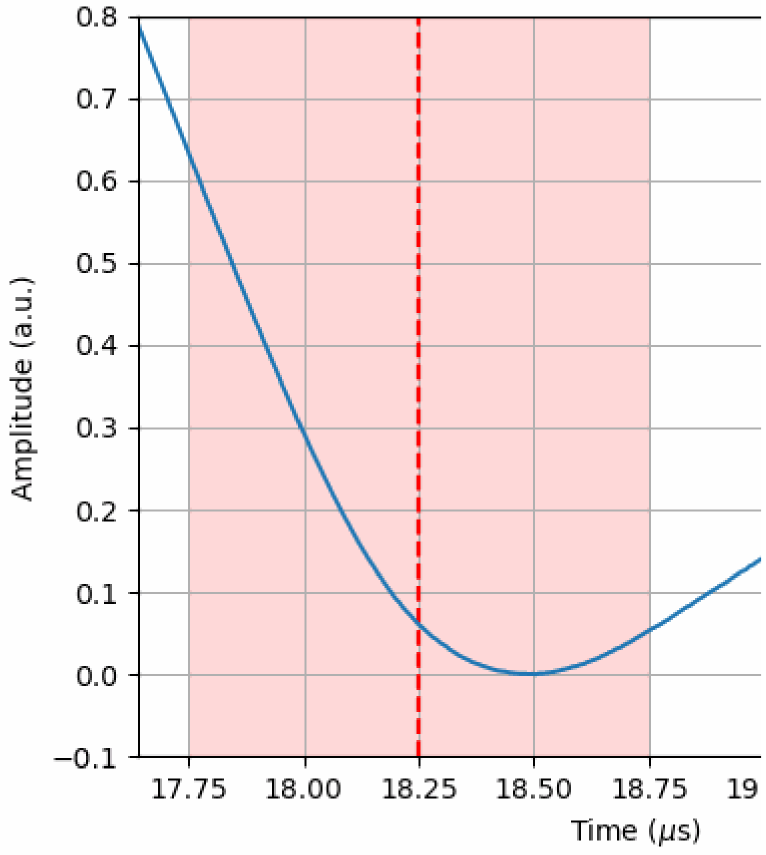


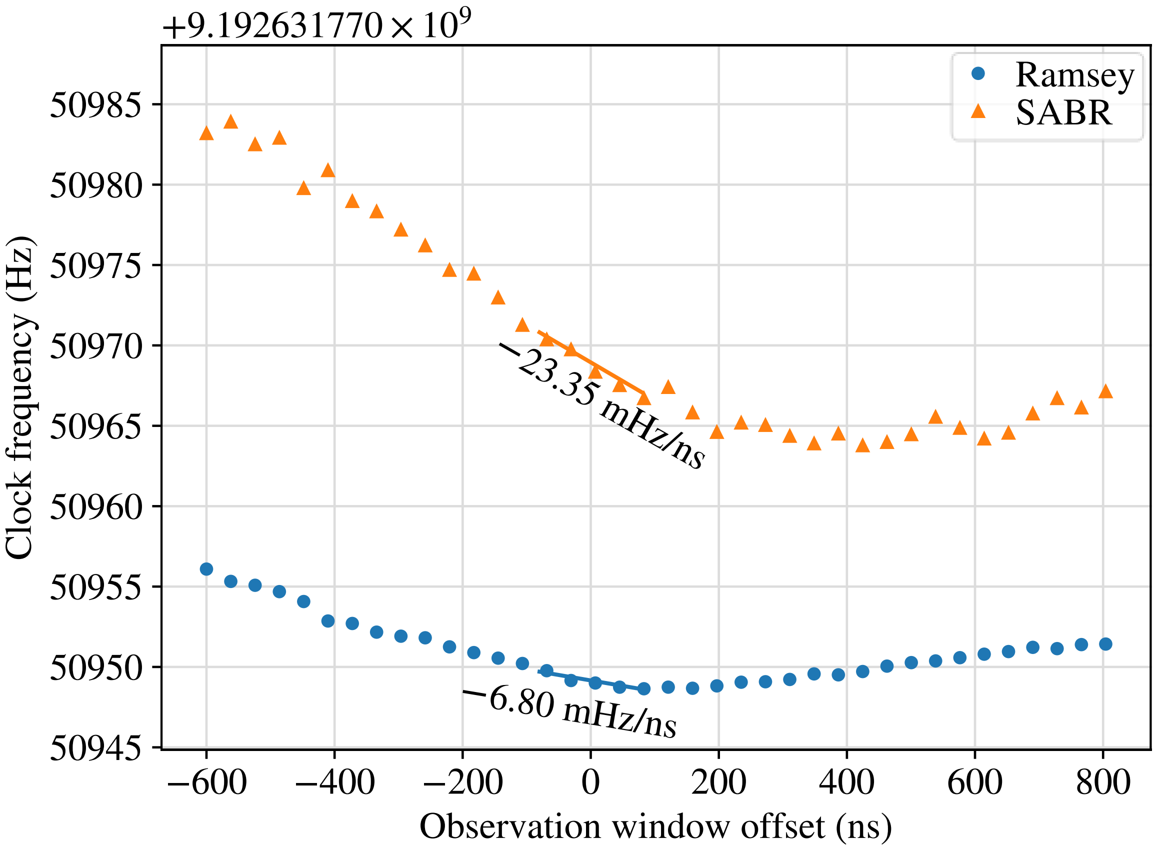
- The fluctuations affected:
  - The ability to measure the light shift
  - The long-term stability of the clock frequency

The measured fluctuations were within 80 ns, comparable with values reported in the literature [13].

[13] M. Fukuoka *et al*., Jpn. J. Appl. Phys. **62** 122005 (2023)

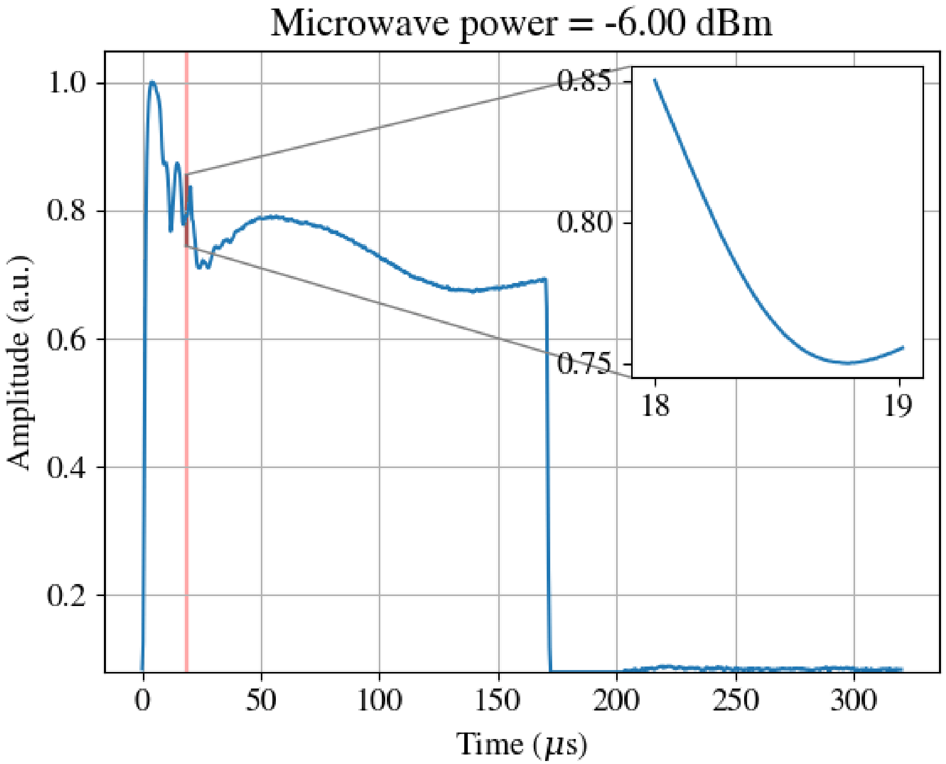
Observation timing effects

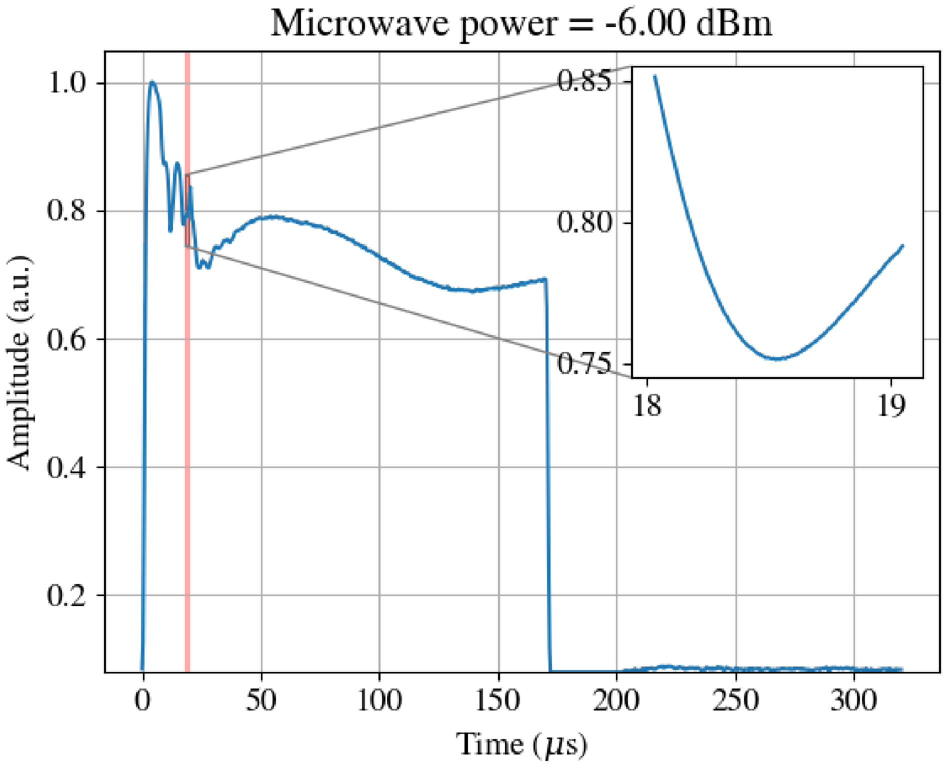




- A detection window position sweep test was conducted to determine its effect on the clock frequency.
  - The objective was to find sensitivity factor.

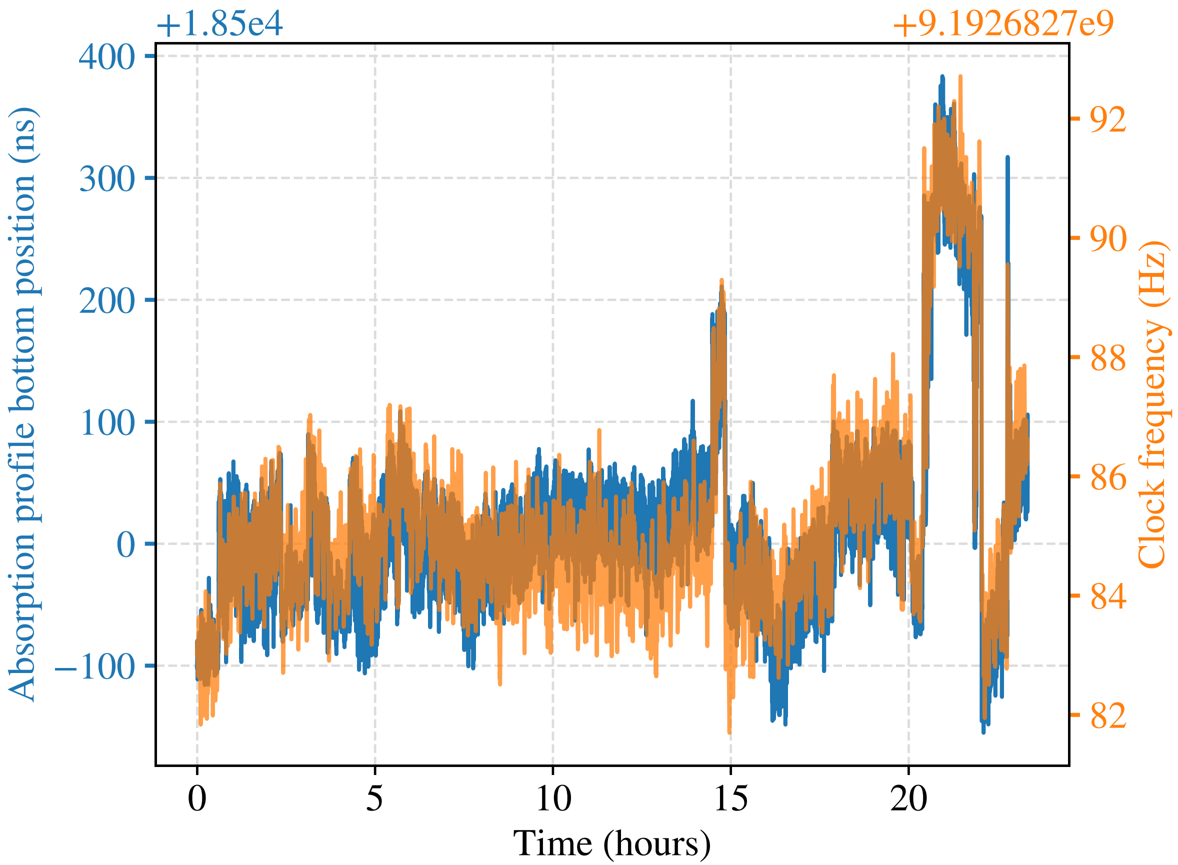
Observation timing effects – Light shift

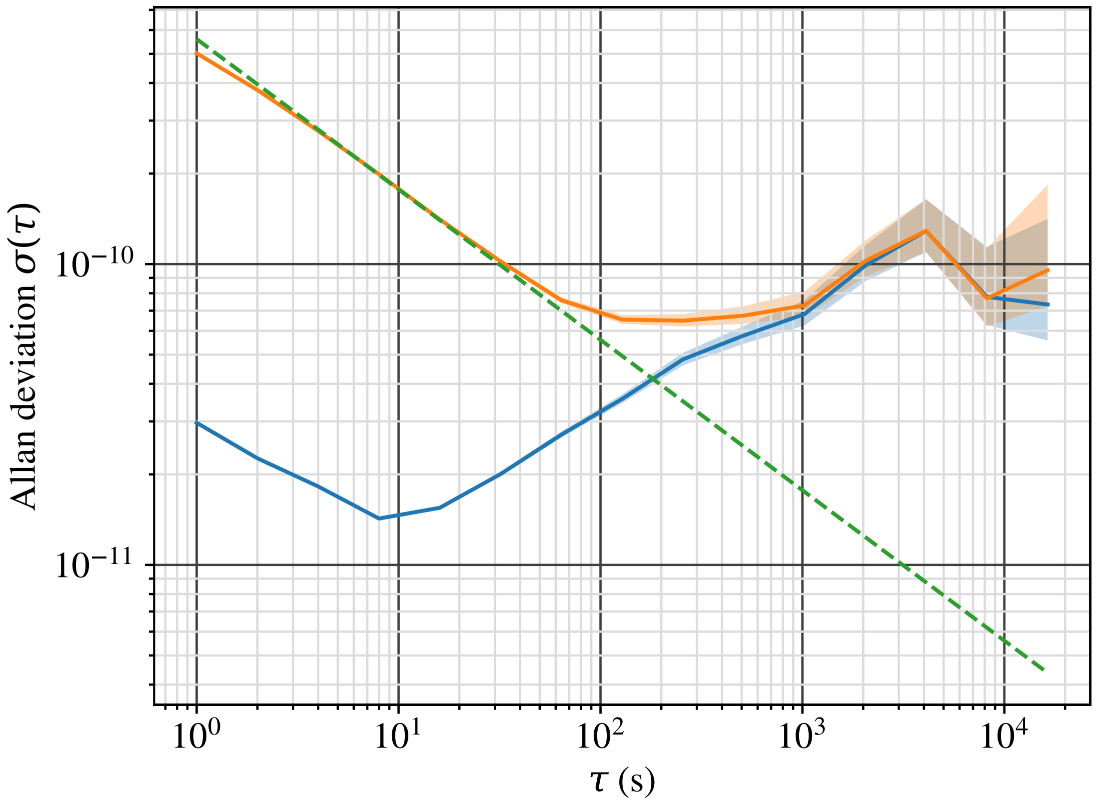




- Light-shift measurements were invalid as the absorption line moved out of the detection window.
- This was the case for microwave power and laser detuning.
- These effects impact both Ramsey-CPT and SABR modes.

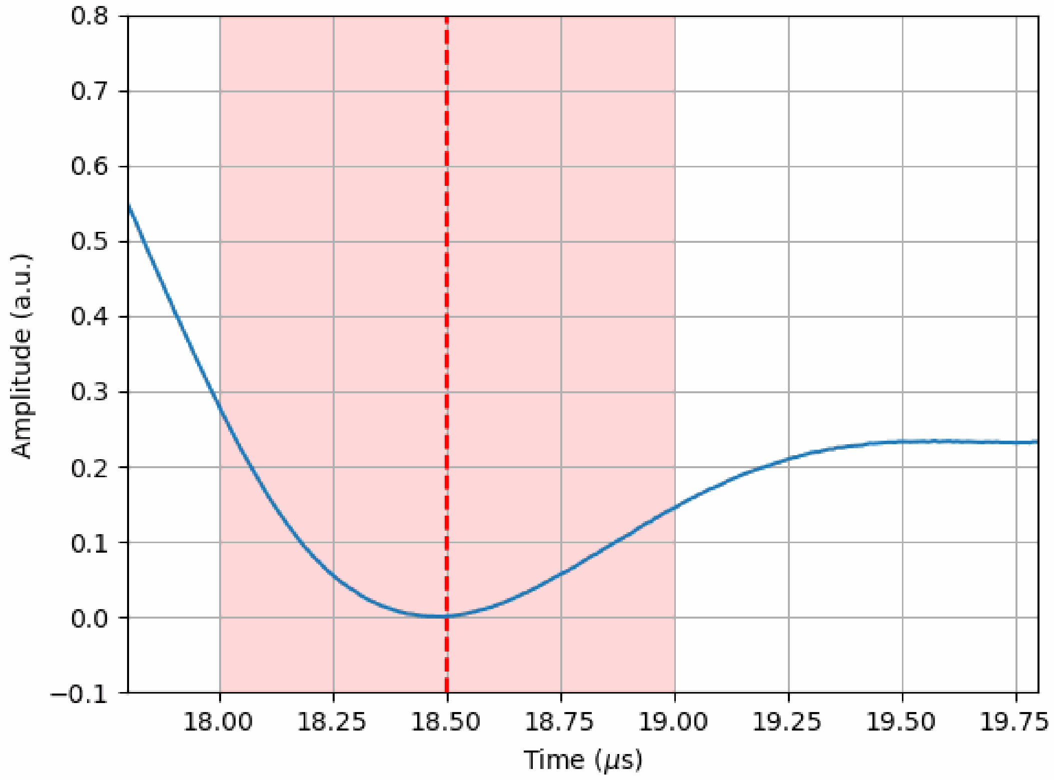
Observation timing effects – Stability

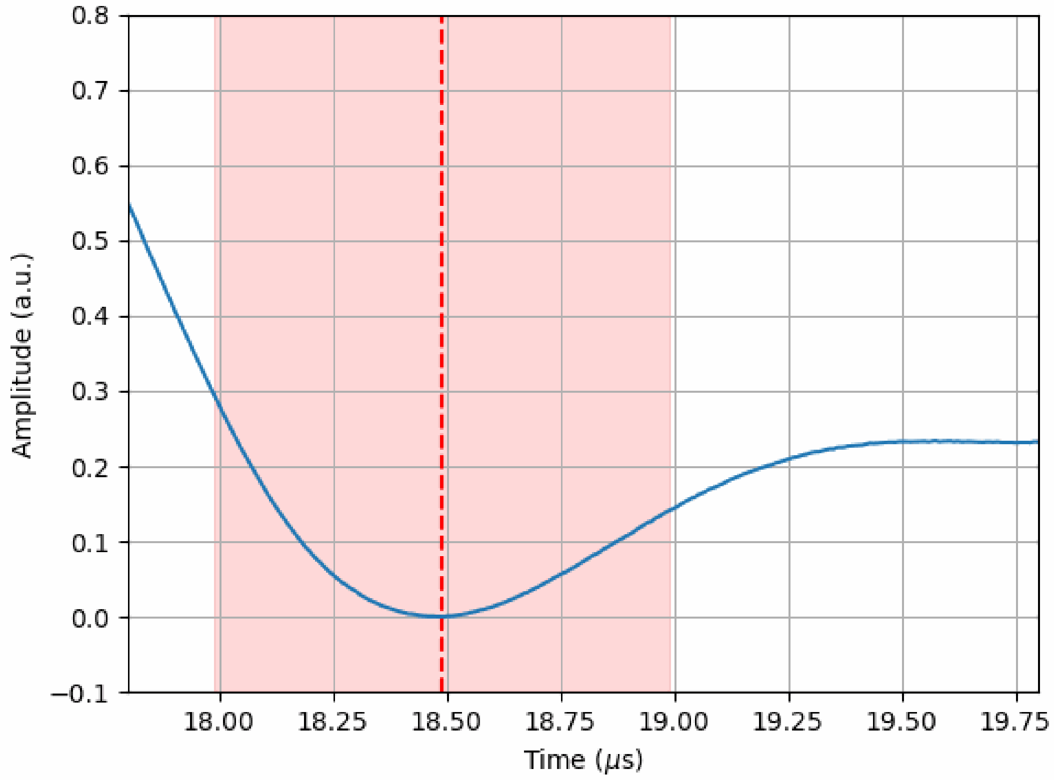




Observation timing effects - Solution

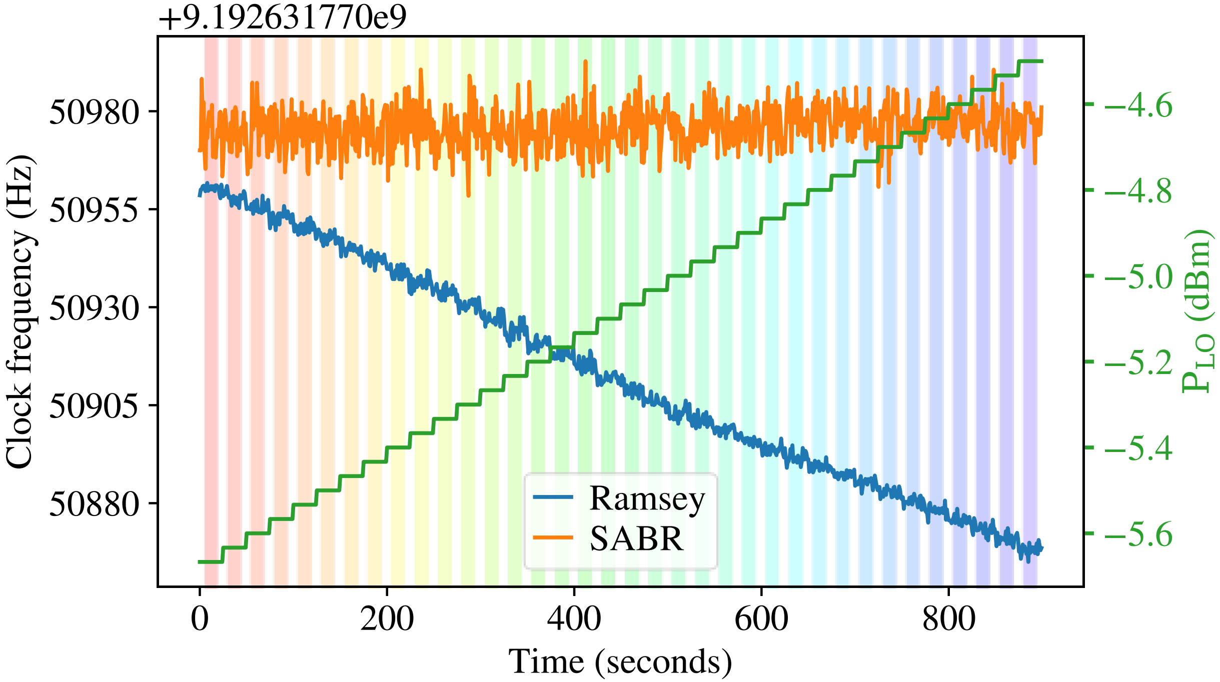
Custom real-time absorption line position tracking system implemented on FPGA.

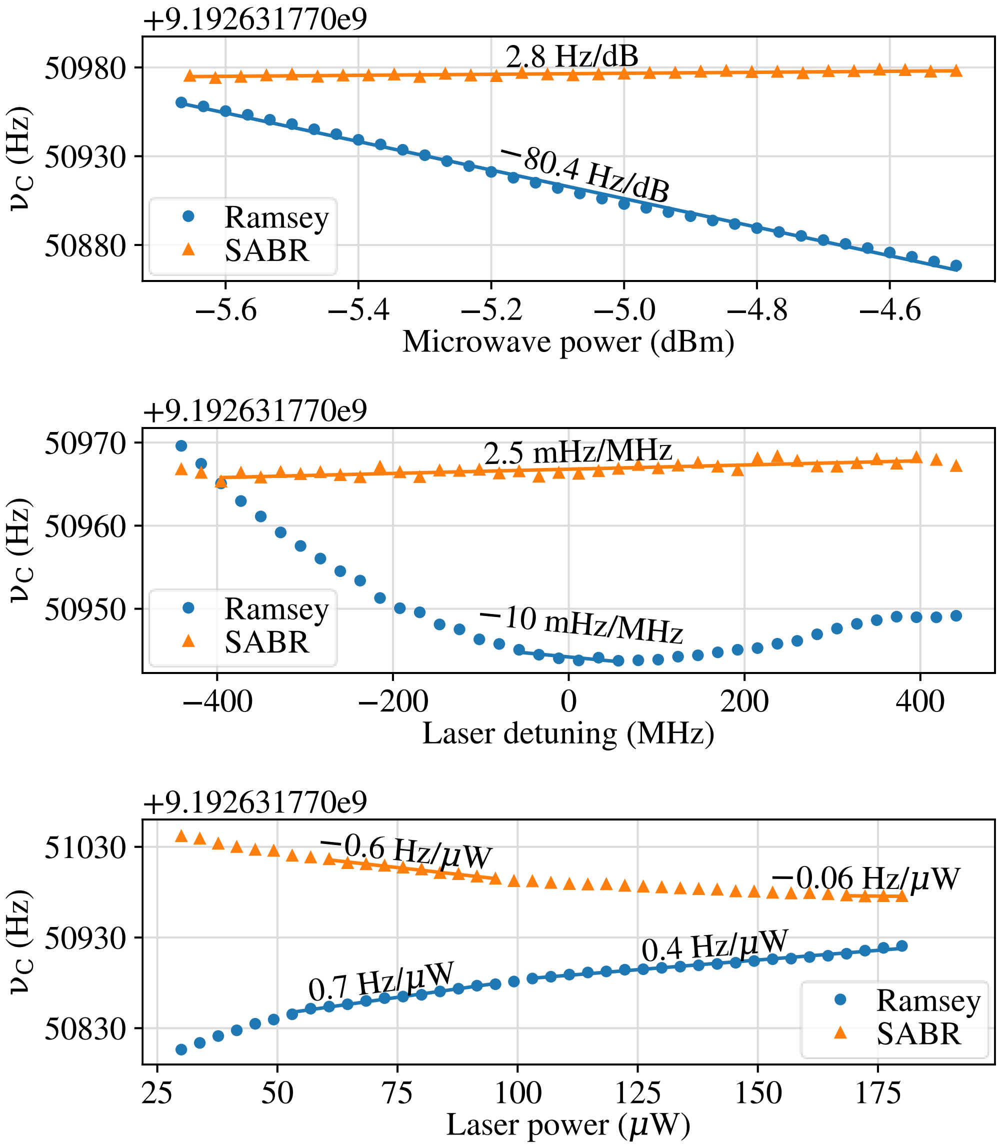




- System detects line position **within a 1 µs** window and then extracts data around it.
  - Method keeps relevant content for atomic signal extraction virtually static.

Observation timing solution – Light shift





Improvement factor:

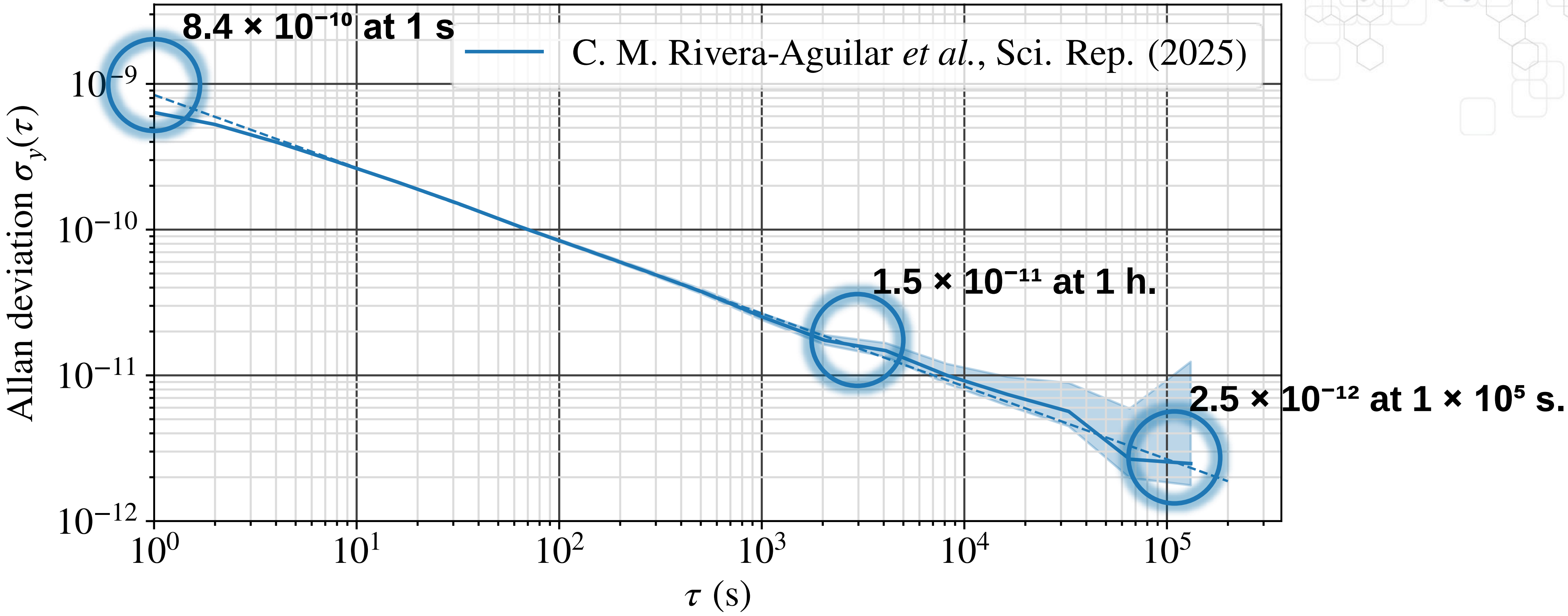
× 28

× 4

× 6.6

[14] C. M. Rivera-Aguilar *et al.*, arXiv:2503.01681 (2025)

Frequency stability

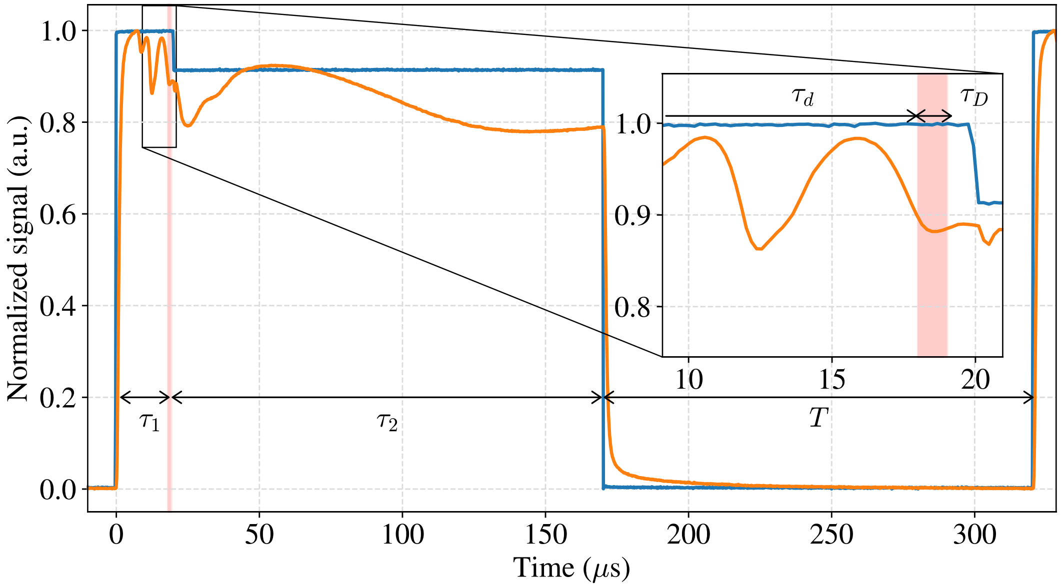


The 1-day stability is comparable to the one obtained with an AOM
(here without laser and microwave power servos) and among the best CPT CSACs reported.

[14] C. M. Rivera-Aguilar *et al.*, arXiv:2503.01681 (2025)

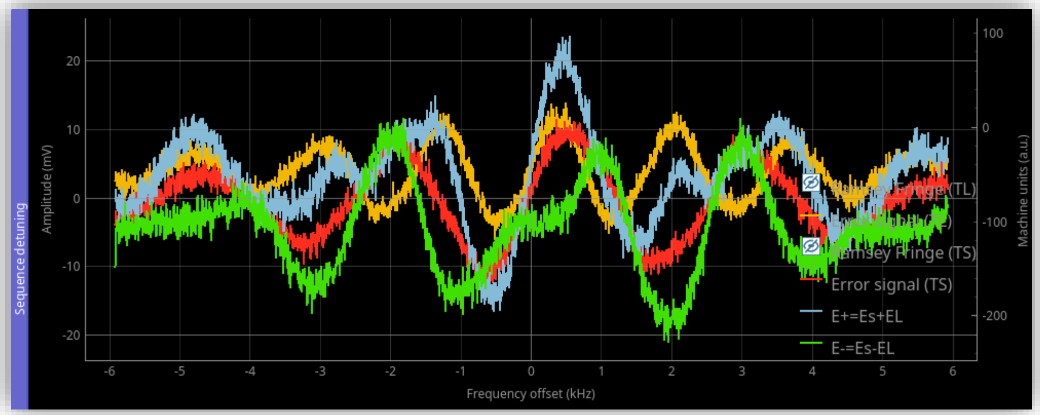
Conclusions

- 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 CSAC with improved stability.



Perspectives

- Improve short-term stability in SABR-CPT operation.
- Perform longer stability tests.



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  - DOI : 10.1038/s41598-025-19732-x