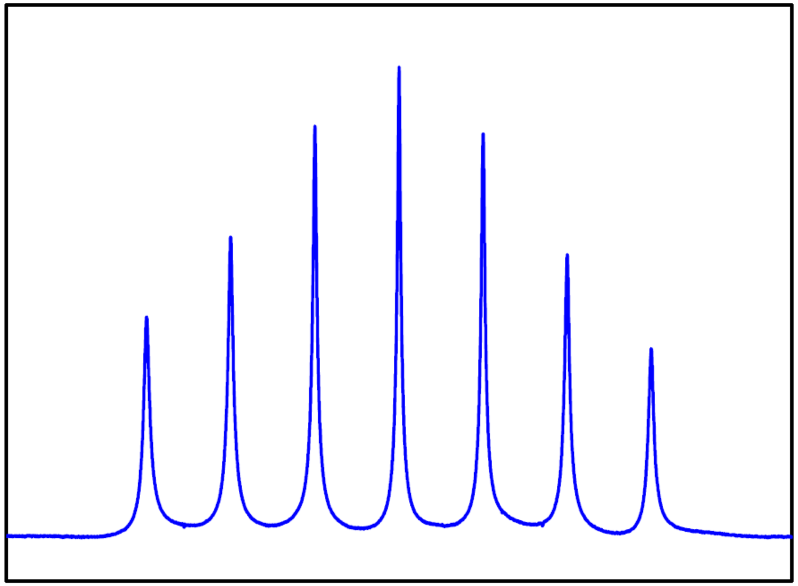
High-performance Cs vapor cell CPT-based atomic clock



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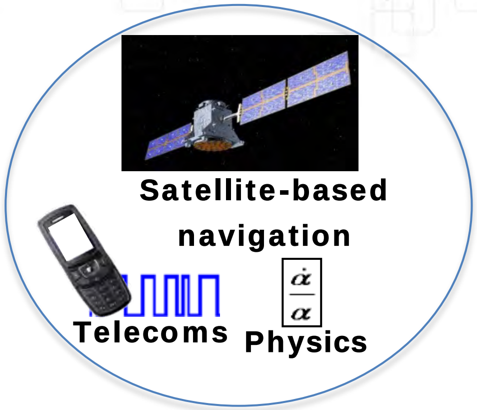
High-performance compact vapor cell microwave clocks

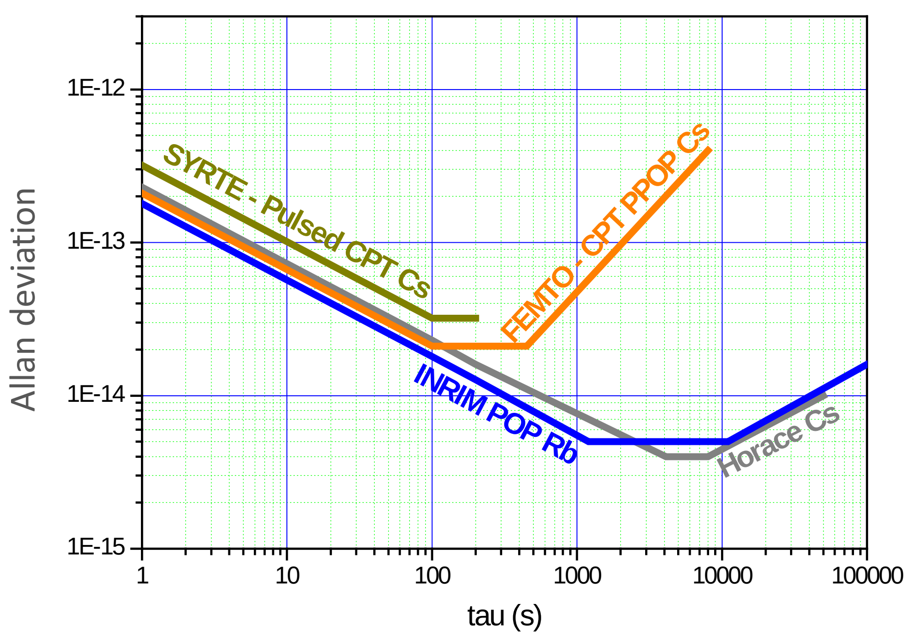
Objectives :

- ***Frequency stability: ~ 10^{-13} @ 1s and in the 10^{-15} range at 10 000 s***
- ***Volume: 10 liters – Power consumption: 10 W***
- ***10 to 100 times better than Rb clocks in a similar size***
- ***Competitive with hydrogen masers in reduced volume and budget***

***Applications**:* **Navigation (spatial), Telecommunication, Defense, Physics**



State-of-the-art: CW Rb clocks, POP Rb clocks, Cold atom « Rubiclock », CPT clocks



Mclocks

1/ POP Rb clock (INRIM+UNINE)
2/ Horace-Rubiclock (SYRTE+MuQuans)
3/ CPT Cs clock (SYRTE+FEMTO-ST)

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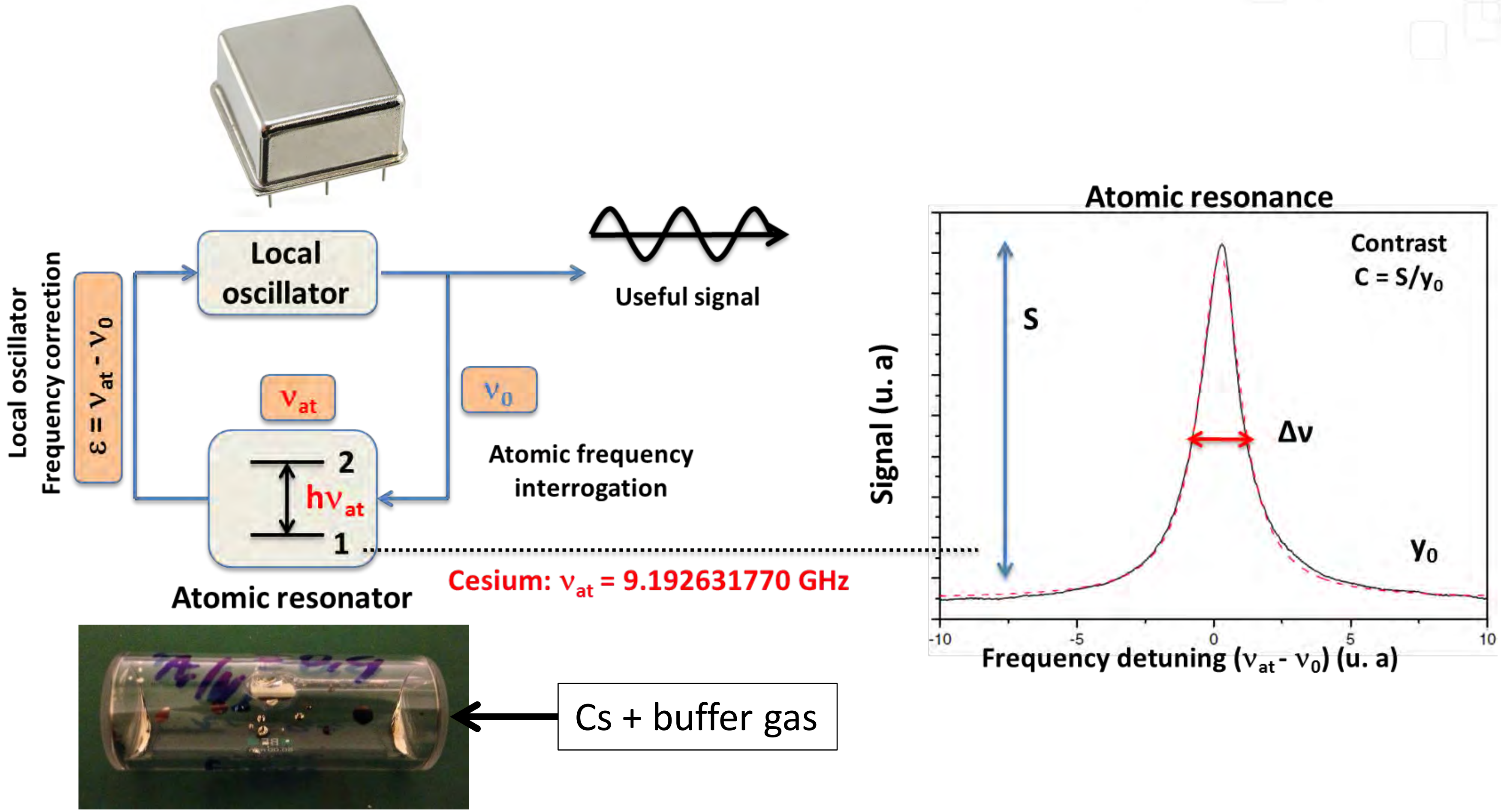
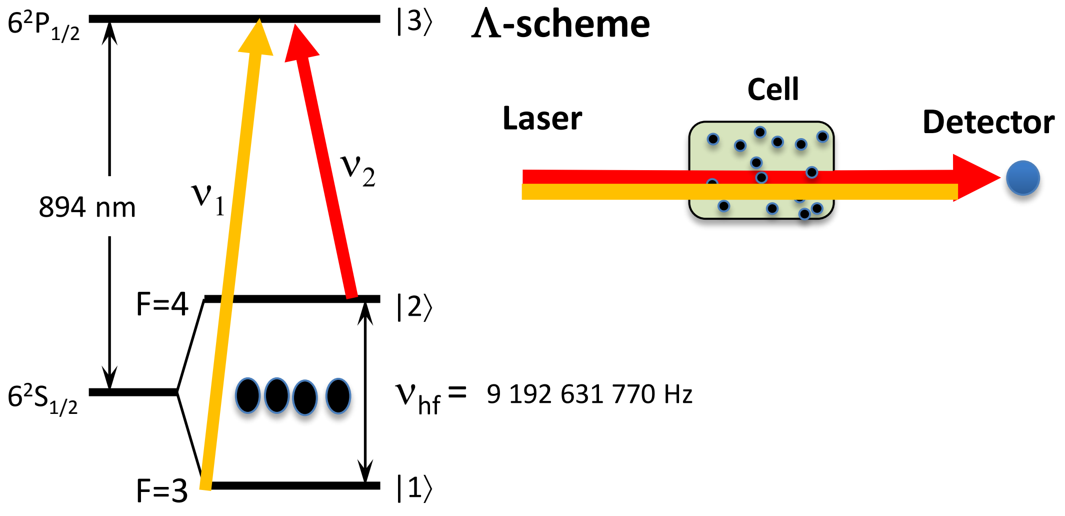
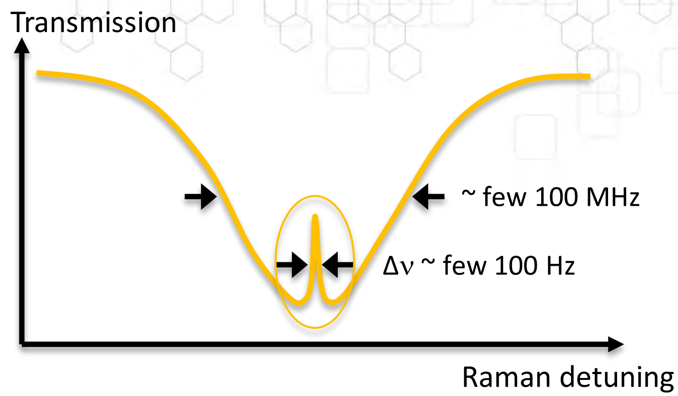
Atomic clocks

Atomic clock : stabilize the frequency of a local oscillator onto an atomic resonance



Coherent Population Trapping basics (Cs atom)





Frequency difference $\nu_1 - \nu_2$ = 9.192 GHz (Raman resonance)

Atoms are pumped in a coherent superposition of both ground-states |1⟩ and |2⟩, not coupled to |3⟩

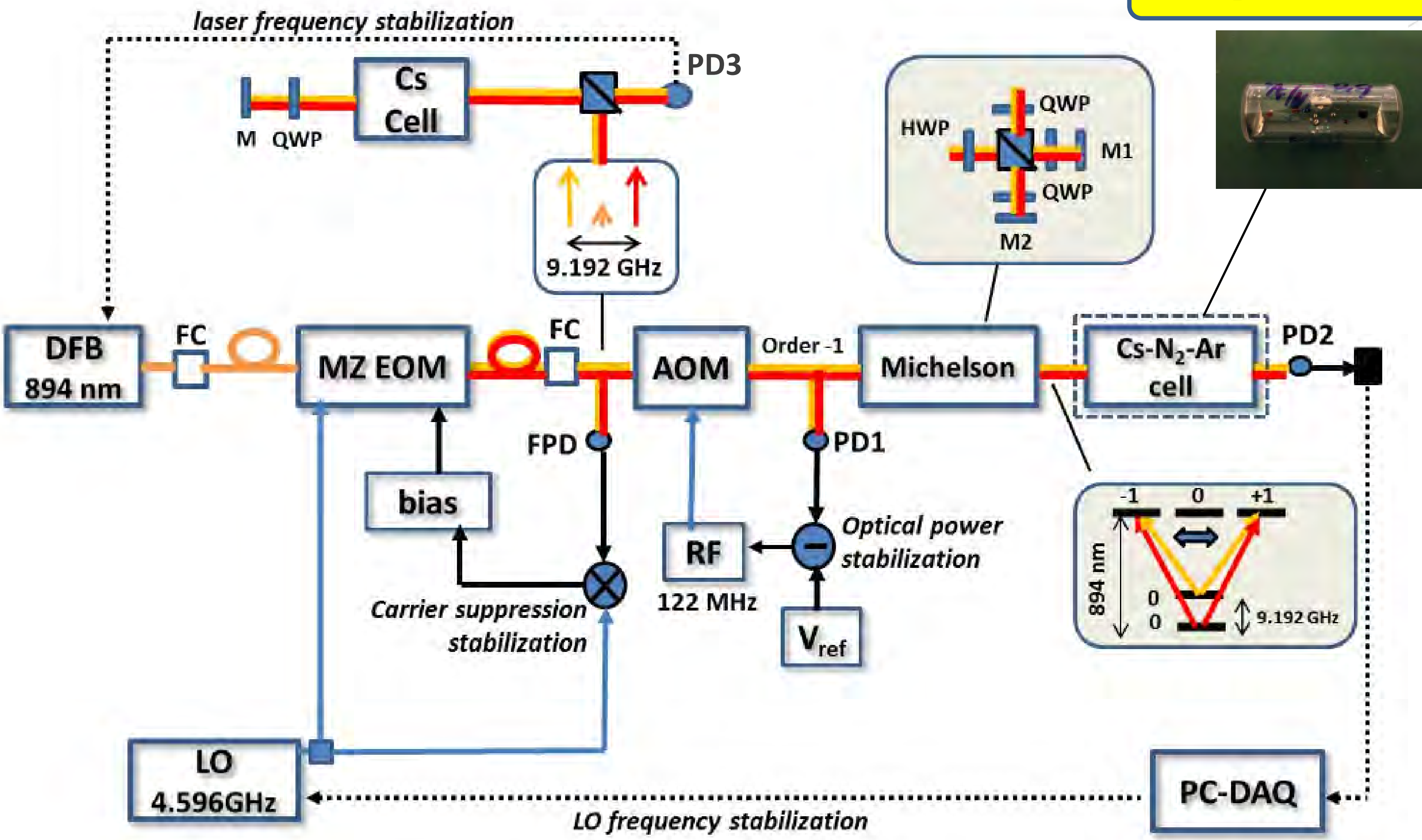
No fluorescence from |3⟩ = Dark state = The vapor transparency is increased

CPT resonance: narrow frequency discriminator

All-optical interrogation: No resonant cavity → Compact clocks

Experimental set-up

Cell N_2-Ar 15 Torr r=0.4



M. Abdel Hafiz and R. Boudot, Journ. Appl. Phys. (2015)

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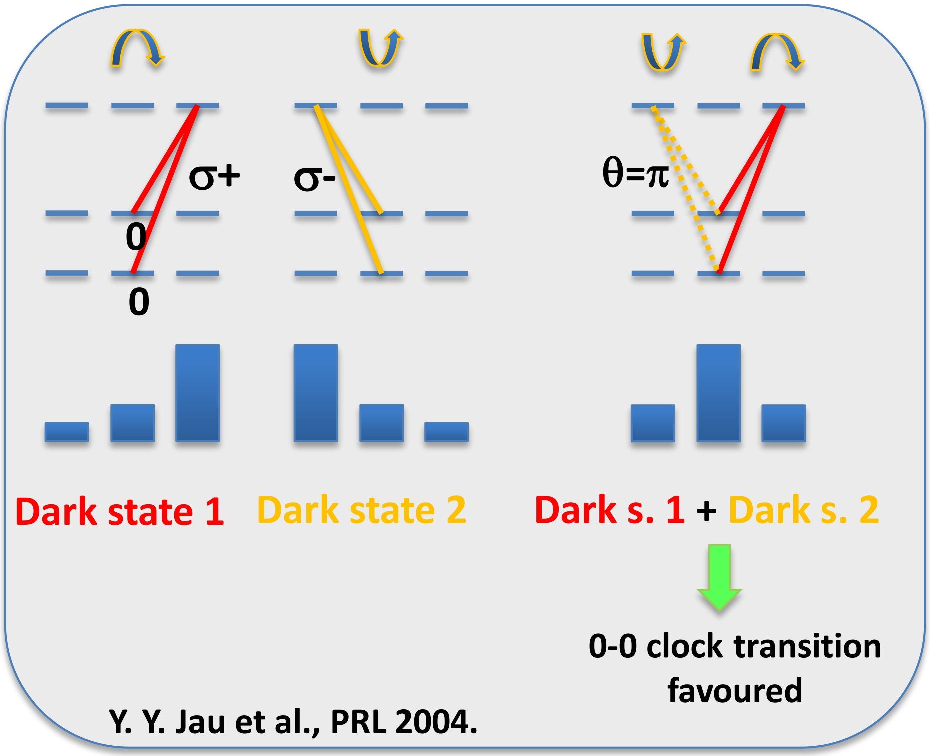
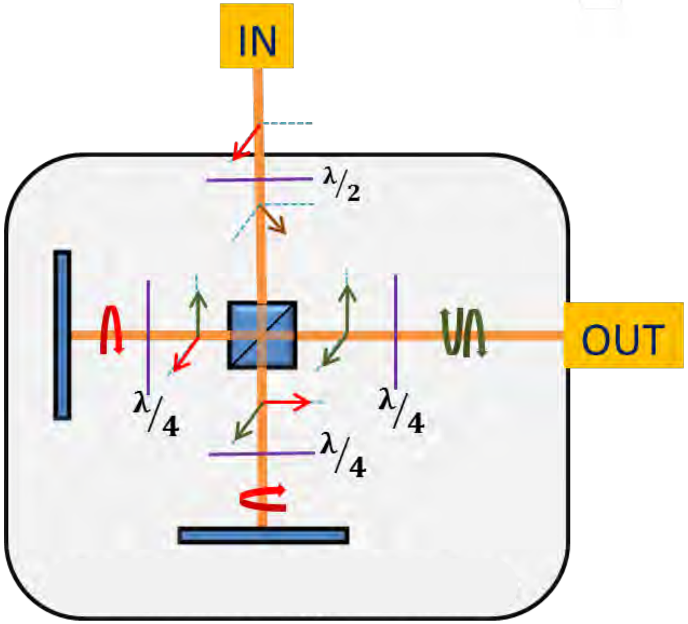
Push-pull optical pumping

Usual CPT clocks = circular polarization ➔ low CPT signals on the 0-0 transition

Push-pull scheme : Atoms interact with a bi-chromatic optical field that alternates between right and left circular polarization at the clock Bohr frequency.

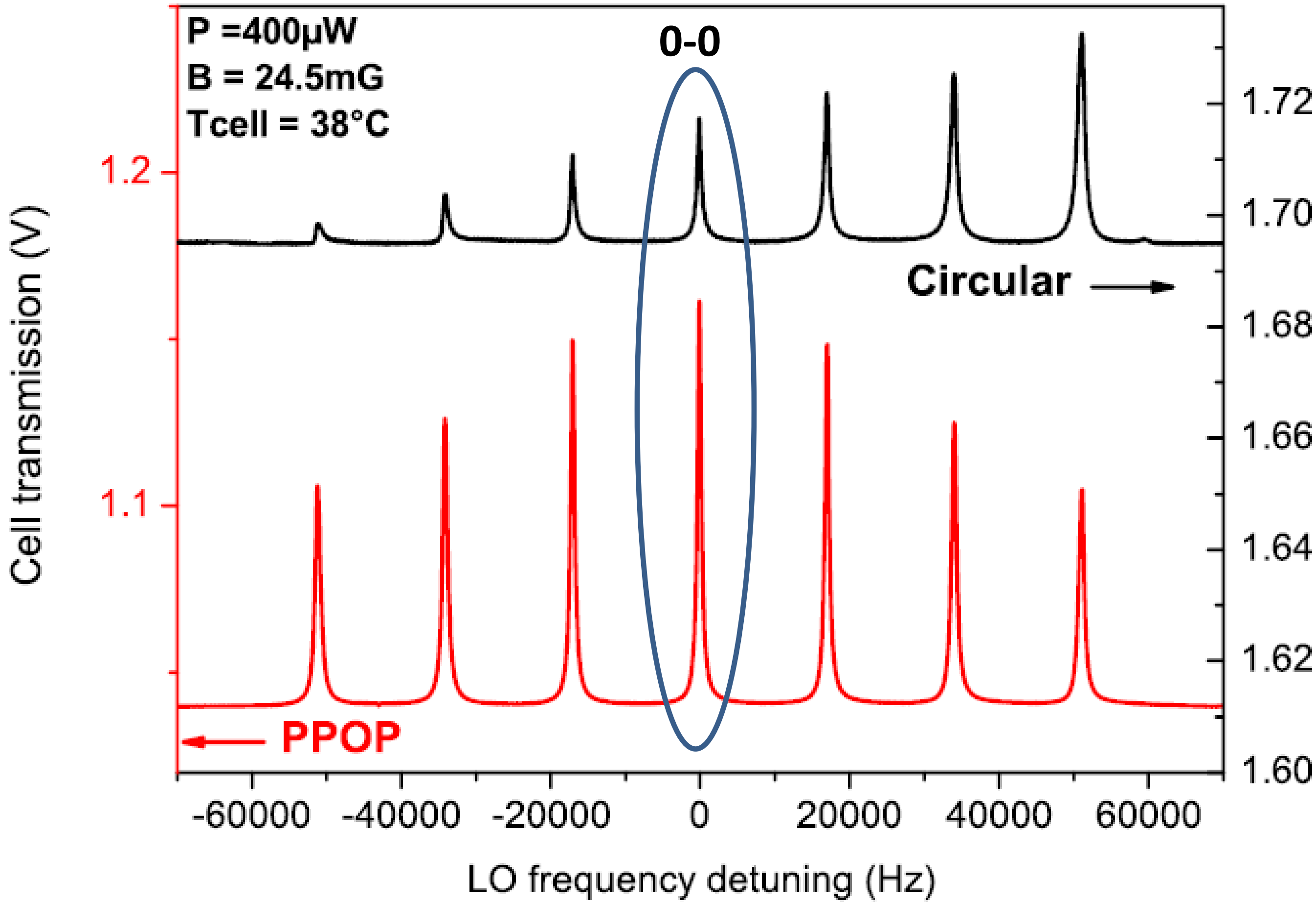




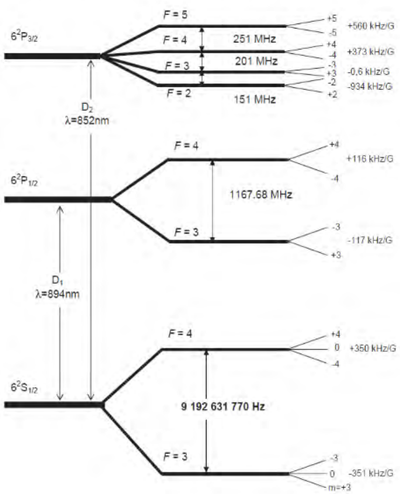
Michelson system :
Delay line + Polarization orthogonalizer

Constructive interference of 2 successive dark states

Zeeman spectrum



Cs D_1 line



The PPOP technique allows to increase greatly the 0-0 clock transition

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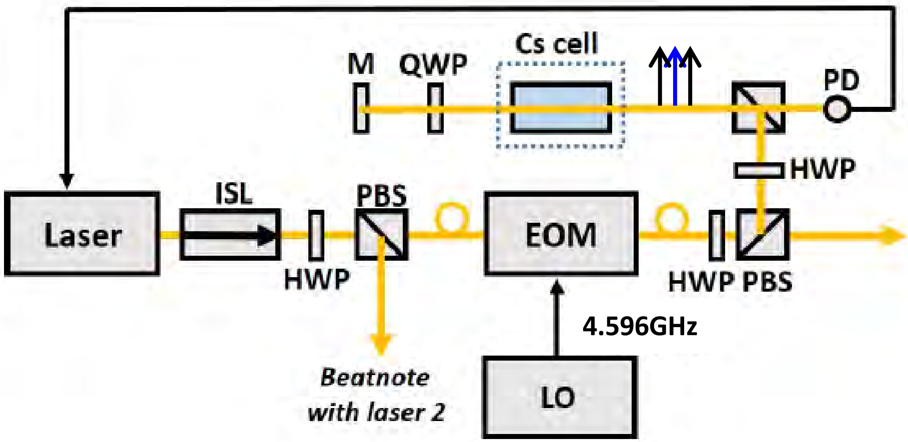
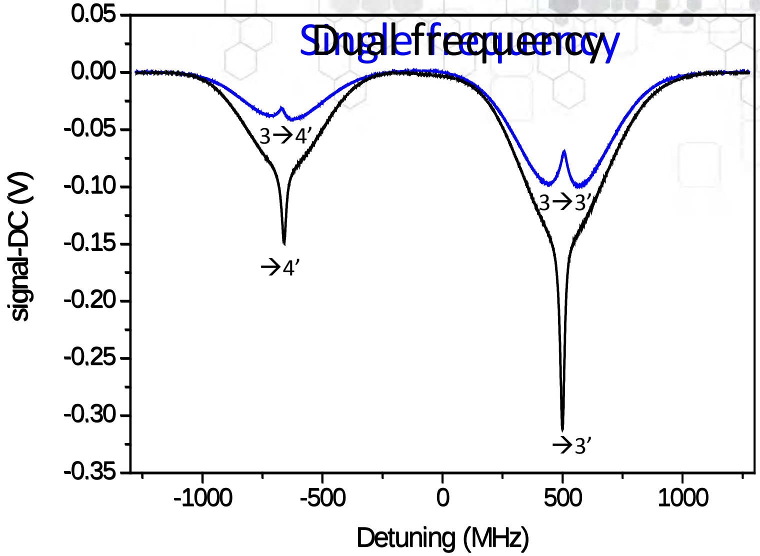
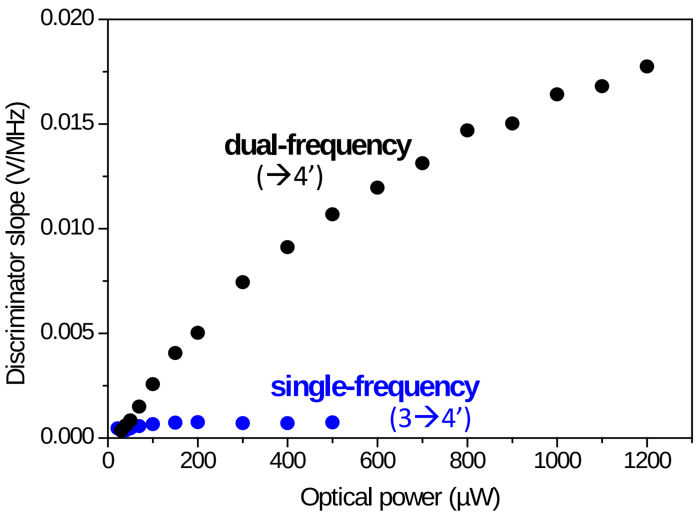
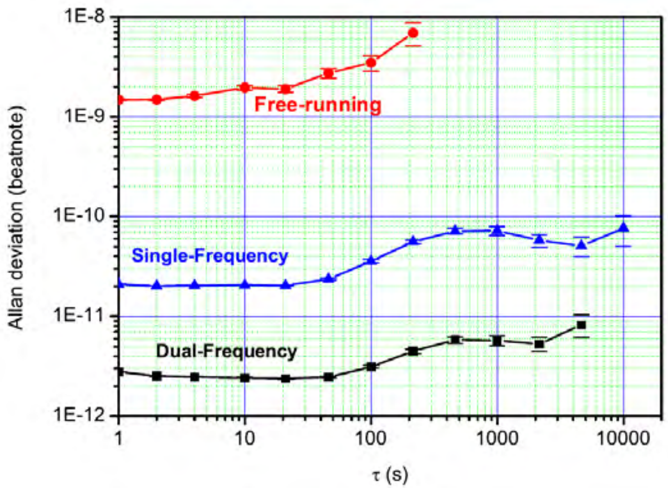
Dual-frequency Doppler-free Cs spectroscopy



M. Abdel Hafiz et al., to be submitted PRA (2016)





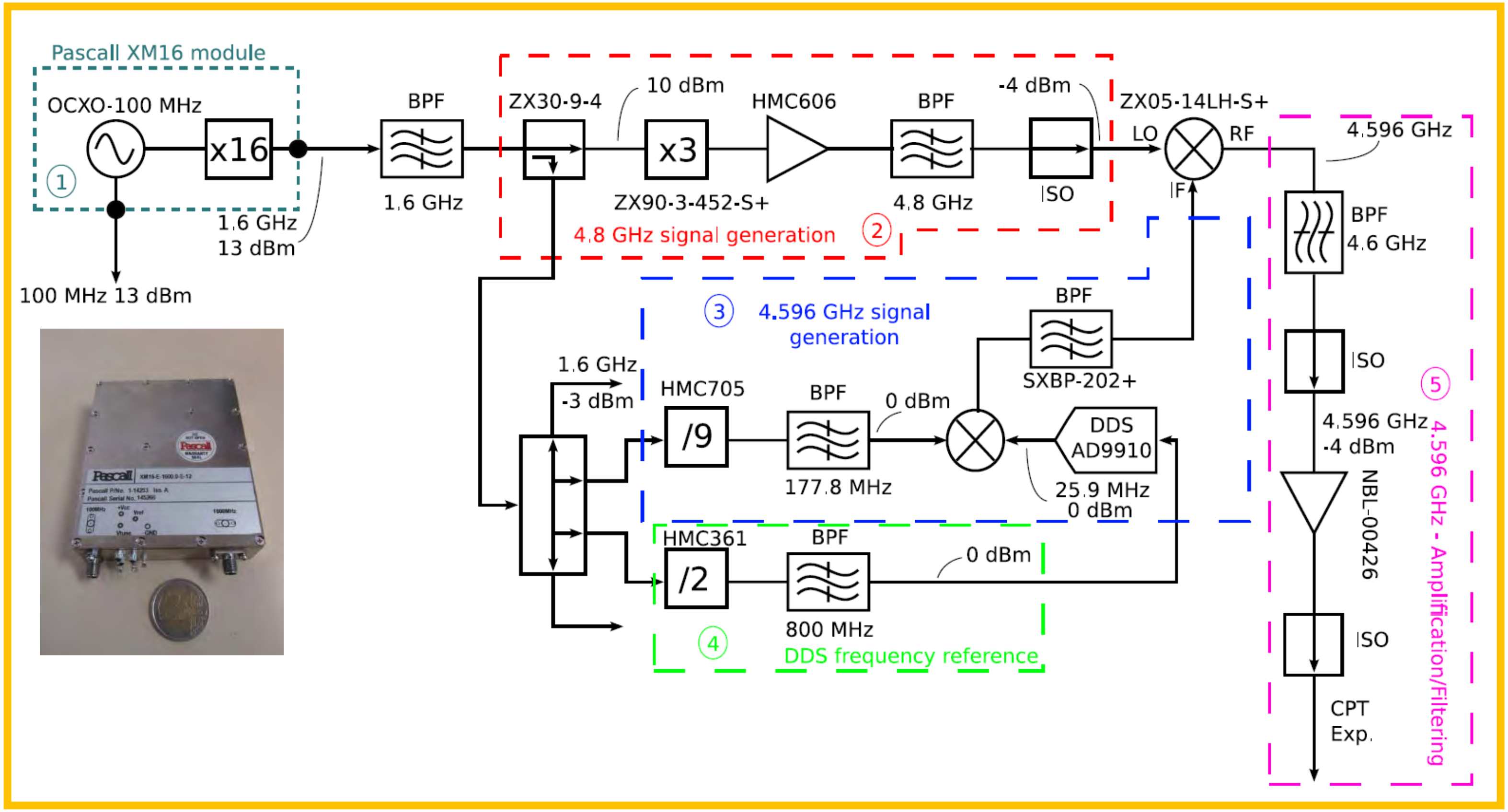


Low phase noise microwave frequency synthesizers

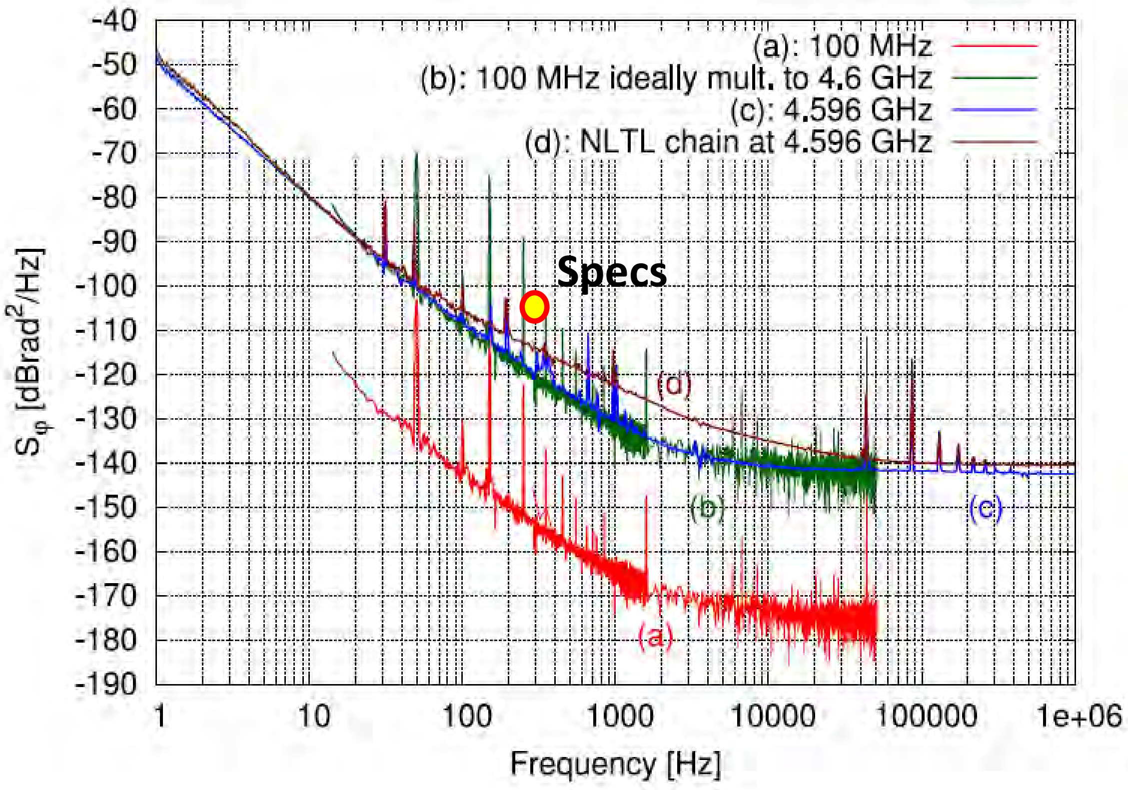
The atomic clock fractional frequency stability can be degraded by the local oscillator phase noise.

Needs: $\sigma_y (\tau) = 10^{-13}$ @ 1 s, S_φ (f = 300 Hz) < -105 dBrad^2/Hz

Frequency multiplication of a 100 MHz OCXO up to 4.596 GHz



Low phase noise microwave frequency synthesizers



Frequency multiplication of a 100 MHz OCXO up to 4.596 GHz without excess noise

Intermodulation effect contribution rejected at the level of 3.1 10^{-14} @ 1 s (close to the clock shot noise limit).

B. Francois et al., Rev. Sci. Instr. 86, 064707 (2015)

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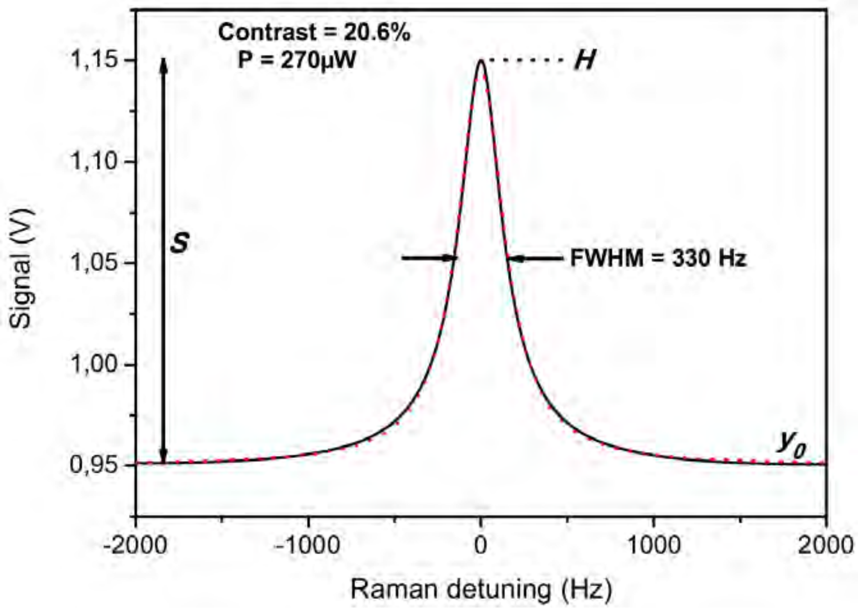
CPT spectroscopy

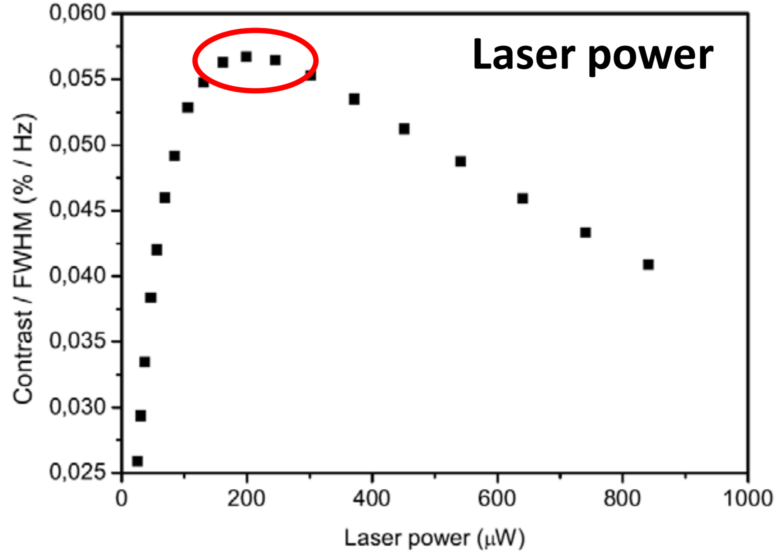
Typical CPT clock signal

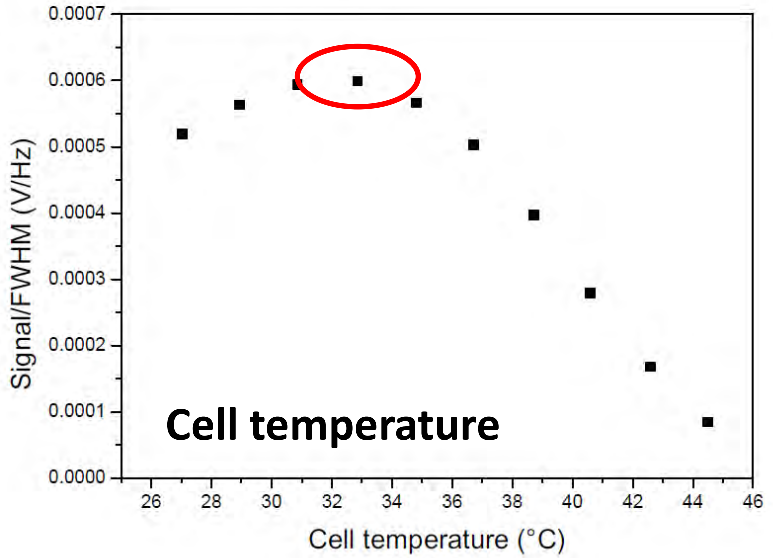


Expected short-term frequency stability

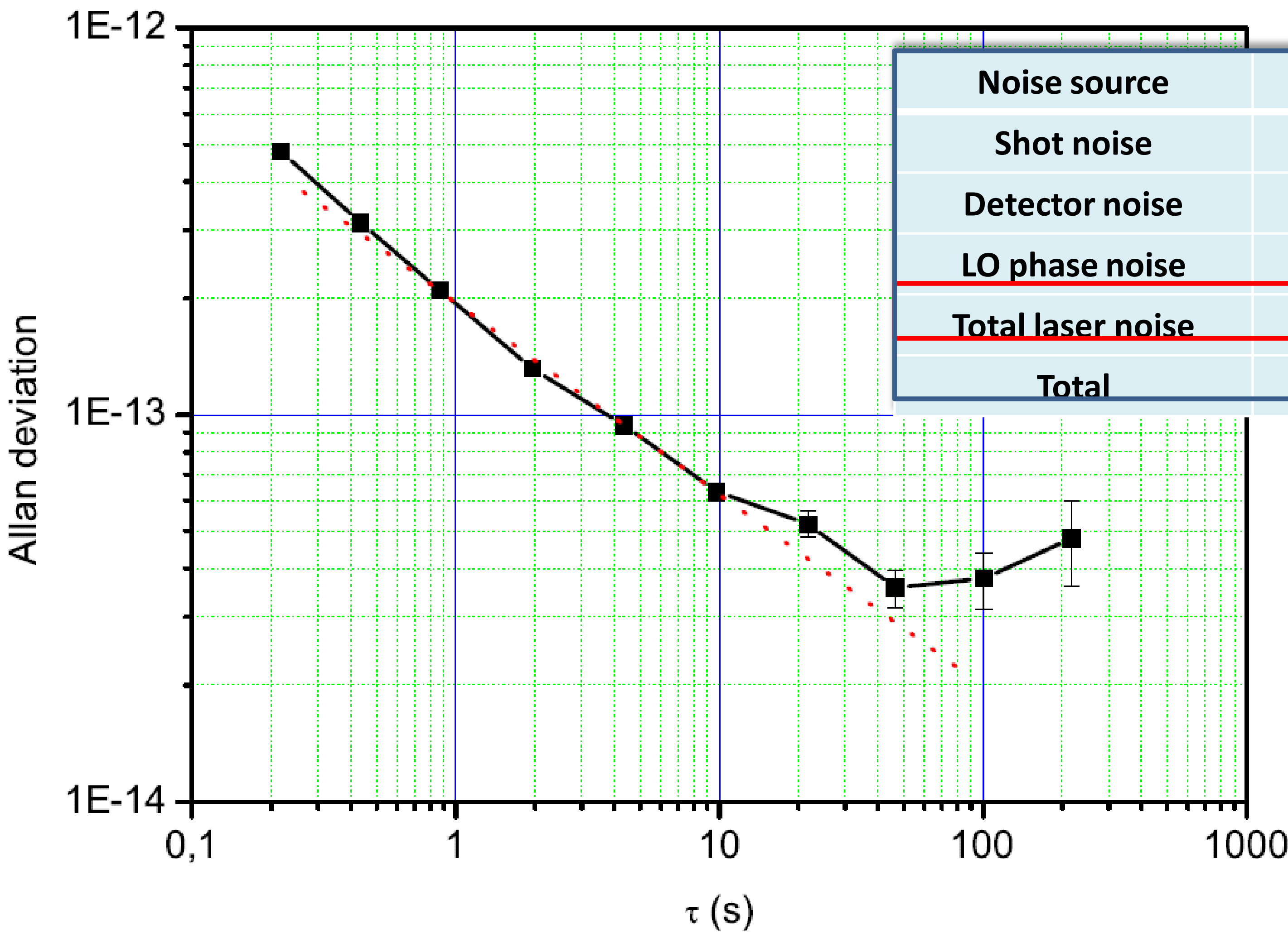
2 10^{-13} @ 1 s

M. Abdel Hafiz and R. Boudot, Journ. Appl. Phys. (2015)





Short-term frequency stability



Noise source	σ (1s)
Shot noise	$8\ 10^{-15}$
Detector noise	$2\ 10^{-14}$
LO phase noise	$3.1\ 10^{-14}$
Total laser noise	$2\ 10^{-13}$
Total	$2\ 10^{-13}$

Short-term frequency stability comparable to best vapor cell clocks

… and still can be improved…!

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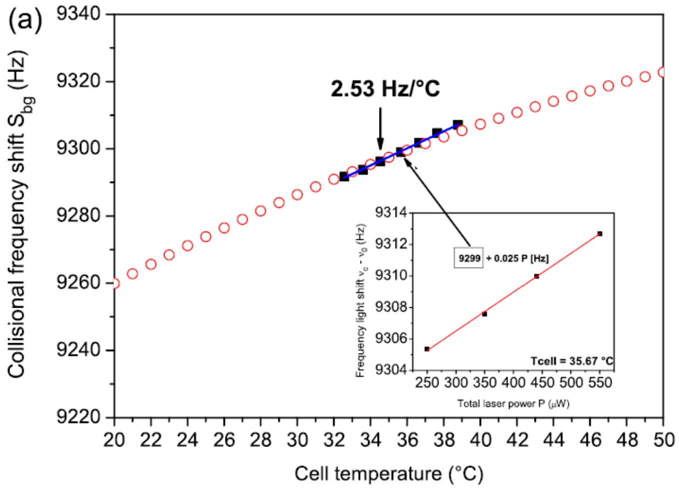
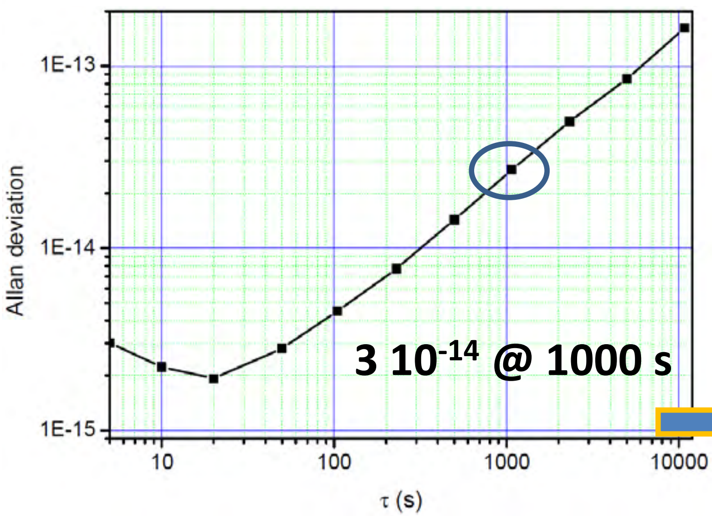
Mid-term frequency stability

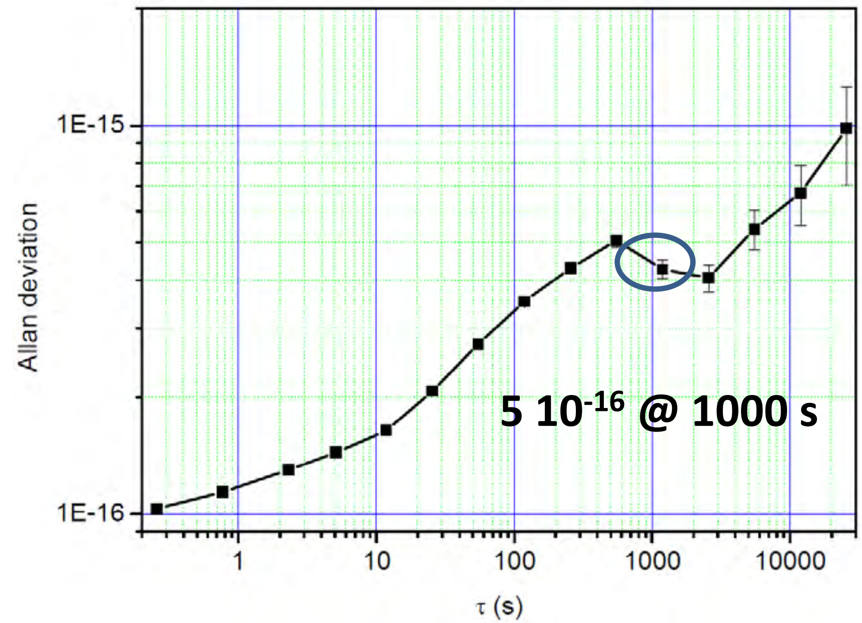
Cell temperature: the presence of buffer gas in the cell induces a temperature-dependent frequency shift of the clock transition.





Zeeman shift contribution

The LO frequency is stabilized onto the 1-1 magnetic field-sensitive Zeeman transition (~ 700 kHz/G)



Will be reduced using a cell with optimized buffer gas mixture (r = 0.6)

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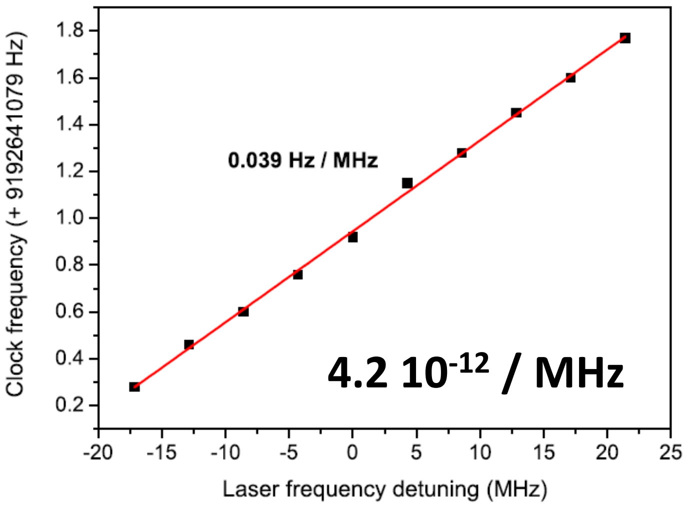
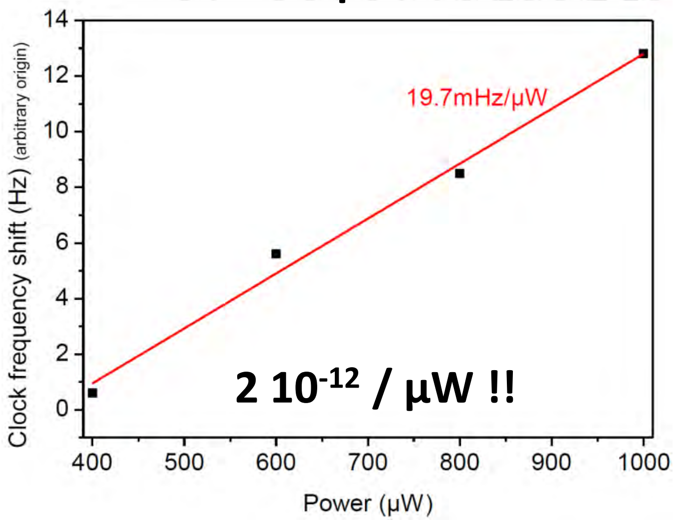
Mid-term frequency stability: laser power

Laser frequency detuning



7 10^{-15} @ 1000 s

Laser power



5 10^{-14} @ 1000 s

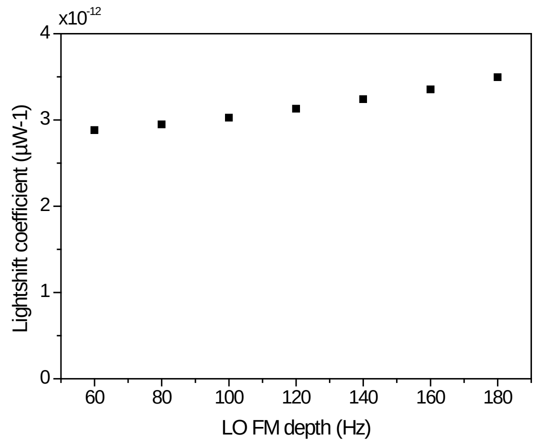
The main limitation to the clock frequency stability at 1000 s comes from laser power. The contribution of the collisional shift is just below. Other contributions are well below.

Kill light shift (1 PhD year..) !!

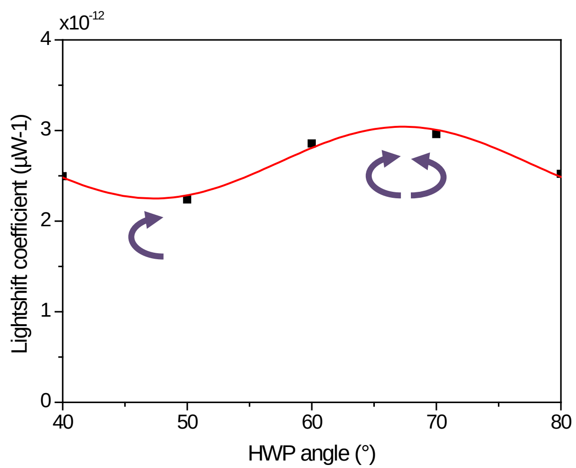
Studies on Light shift (in CW regime)

The impact of several experimental parameters onto the light shift slope was studied.

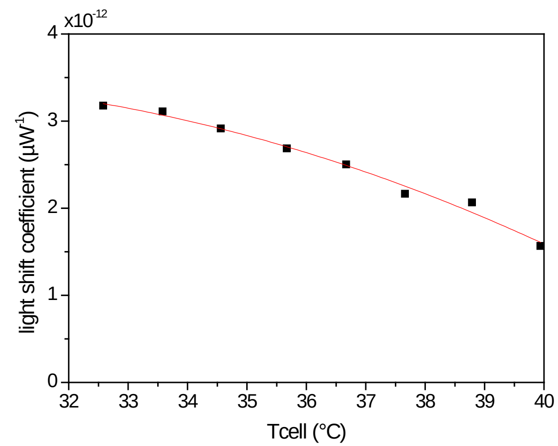
LO modulation index



Push-pull polarization asymmetry



Cell temperature



No experimental condition satisfying simultaneously a zero light shift sensitivity and a good short-term stability was found

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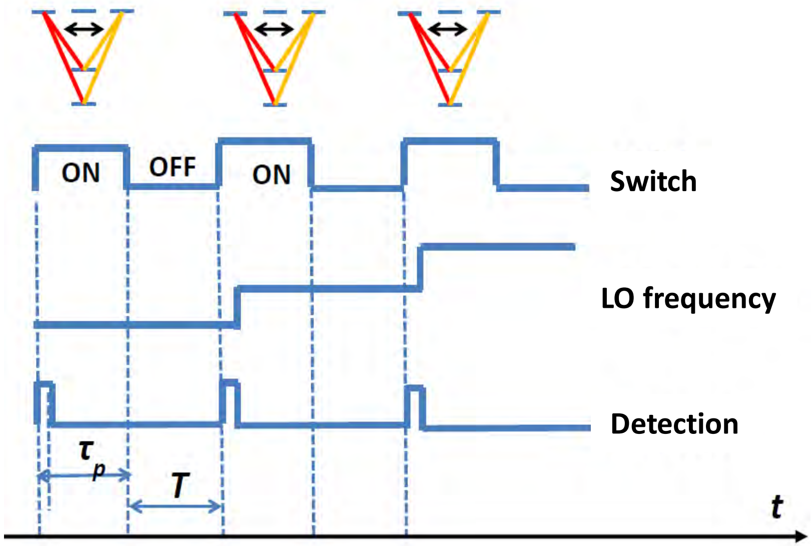
Towards a pulsed CPT-PPOP clock ?

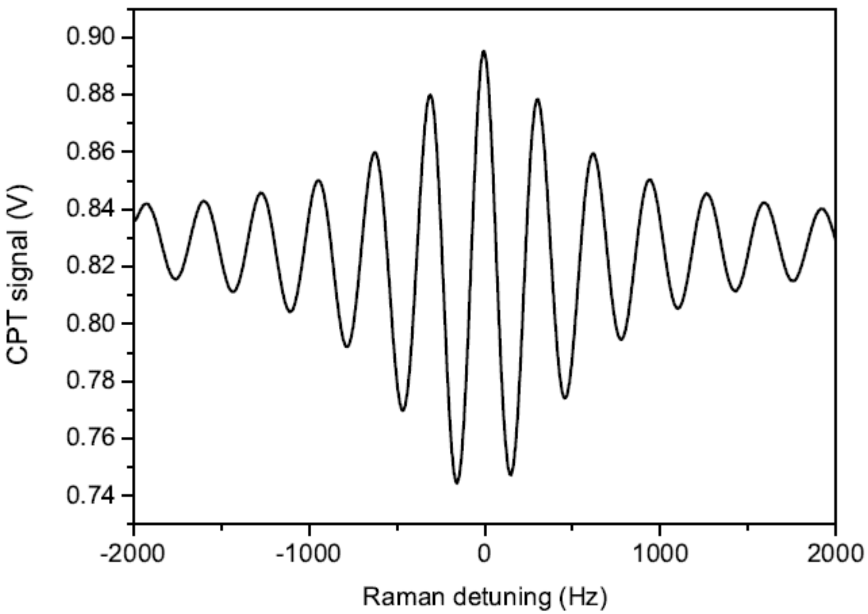
Atoms interact with a sequence of CPT optical pulses
Each pulse is used both for CPT pumping and CPT detection
Each pulse is separated by a free-evolution time T in the dark.

Detection of narrow (1/2T ~ 100 Hz) and high-contrast Ramsey fringes
Reduction of the light shift contribution (~10 in our experiment)

Ramsey-CPT sequence



Ramsey-CPT fringe



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Conclusions and perspectives

Development of a CW-regime CPT-based Cs vapor cell clock
- push-pull optical pumping for enhanced clock signal
- original dual-color Doppler-free spectroscopy laser frequency stabilization
- high-performance microwave frequency synthesizers
- detailed CPT spectroscopy and mid-term stability investigations

Fractional frequency stability: 2 10^{-13} $\tau^{-1/2}$ up to 100 s averaging time
- Mid-term performances limited by laser power effects
- Studies to « kill » light shift in progress
- Ramsey-CPT clock : possible future alternative solution
- New cell with optimized buffer gas mixture

Ideal platform for physics experiments
- Study of wall-coated cells
- Relaxation time measurements
- Buffer-gas filled cells
- Microcells