Cavity-stabilized lasers
AG First-TF 2015

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l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

Outline

1 Principles

2 State-of-the-art

3 Projet First-TF : long cavity

Content

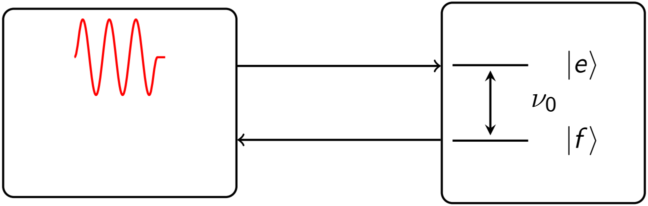
1 Principles

2 State-of-the-art

3 Projet First-TF : long cavity

Laser stabilisation

Optical atomic clock: lock a laser on a narrow atomic resonance



Atomic resonance line-width $\simeq$ 1 Hz $\Rightarrow$ requires a laser line-width $\ll$ 1 Hz

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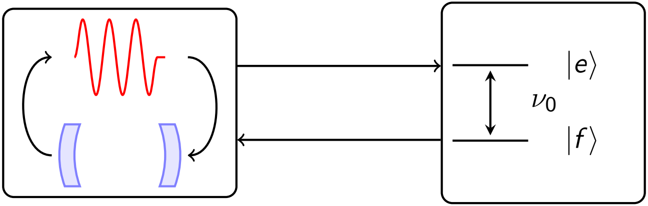

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Solution : stabilize the laser on an optical resonator (Fabry-Perot cavity)

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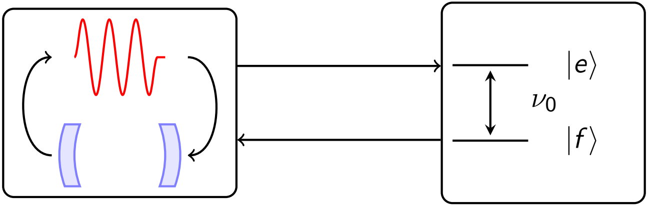

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Challenges

1. Lock the laser on the top of the resonance

   Cavity line-width = 1 to 10 kHz $\Rightarrow$ pin-point at 10^{-5}

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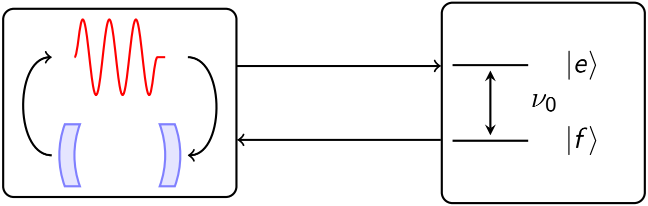

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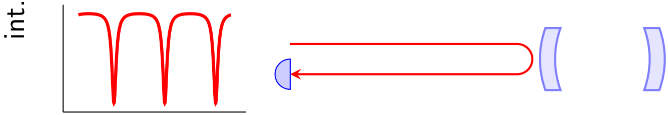
   Cavity line-width = 1 to 10 kHz $\Rightarrow$ pin-point at 10^{-5}

2. When done, the laser follows the fluctuation of the cavity δL

$$\frac{\delta\nu}{\nu} = \frac{\delta L}{L}$$

   L = 10 to 50 cm $\Rightarrow$ $\delta L \simeq 0.1$ fm

Challenge 1: Lock the laser on the cavity



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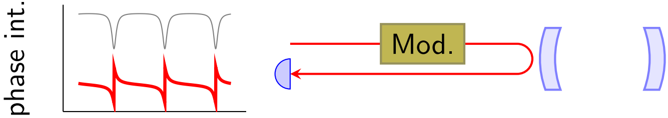

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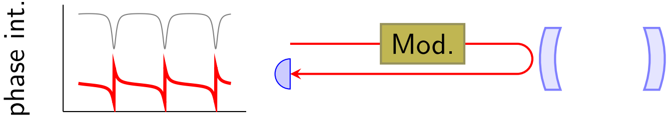

Lock technique: Pound Drever Hall

- Phase modulate the input laser beamer
- Measure the phase shift of the reflected beam by beating with the modulation sidebands

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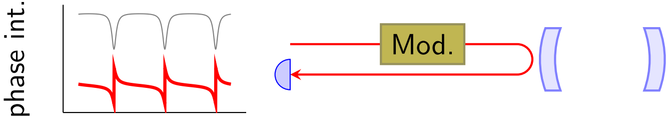

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Noise sources:

- Electronic noise
- Photon shot noise
- Residual amplitude modulation

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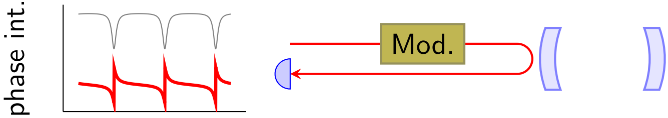

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Conclusion:

- Narrow resonance helps ⇒ high finesse and long cavity
- **Quality of the lock usually not a limiting factor**

Challenge 2: Reduce length fluctuation of the cavity

Aim: reduce length fluctuations of the cavity to $\delta L \simeq 0.1$ fm

Sources of length fluctuations

- Temperature fluctuations

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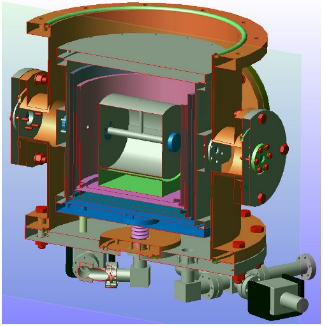

Solutions

- Thermal shields
  (100x damping per shield)

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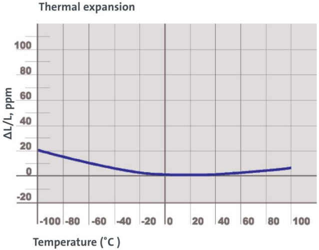

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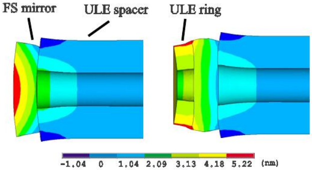
- ULE rings on silica mirrors



T. Legero, JOSA B **27** 914 (2010)

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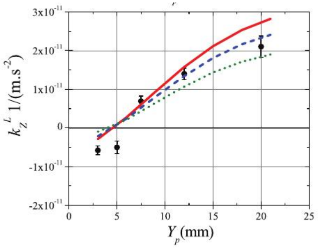

J. Millo, Phys. Rev. A **79** 053829 (2009)

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- Vibration insensitive design
- Anti-vibration tables

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Solutions

- Vacuum operation $P < 10^{-8}$ mbar

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- Long cavity

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- Low mechanical loss materials
  $\Leftrightarrow$ pure materials
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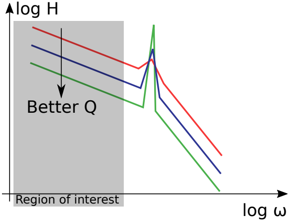
Dominant contribution to the laser noise

Thermal noise – in depth

Spectral point of view

- Excitation of mechanical vibration modes of the cavity by thermal agitation
- Reduced when the resonances are sharper
  ⇔ high mechanical quality factor
  ⇔ low loss material
- Difficult to apply in practice



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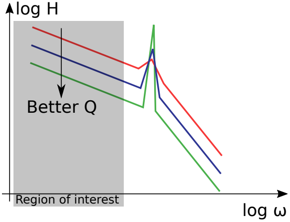
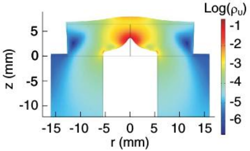


Fluctuation-dissipation point of view

- Mechanical strain energy + mechanical loss
  ⇒ Energy dissipation ⇒ Fluctuation
- Easily modeled with FEM
- ⇒ Coating ≫ Mirror ≫ Spacer



T. Legero, JOSA B **29** 178 (2012)

K. Numata, Phys. Rev. Lett. **93**, 250602 (2004)

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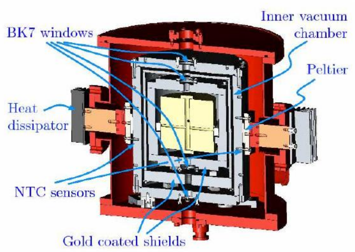
At SYRTE – 2010

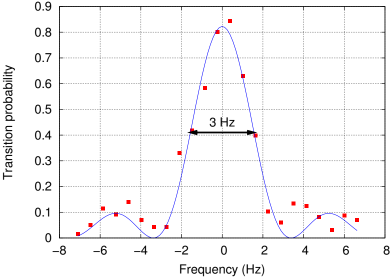
Sr clock laser

Hg clock laser



- ULE spacer, 10 cm long and fused silica mirrors
- Design: horizontal (Sr, 1.5 μ) and vertical (Hg)
- Thermal noise floor around 5×10^{-16}.
- Not at inversion of CTE $\Rightarrow$ 3 layers of thermal shielding (short term temperature fluctuations in the nK range, $\tau = 4$ days)
- Residual drift up to a few 100 mHz/s (feed formard compensation below 1mHz/s)
- Long term drift 56 mHz/s

Single scan of the
$m_F = 9/2 \longrightarrow m_{F'} = 9/2$ transition



- Contrast close to 90%
- Fourier limited at 3.2 Hz
- $Q = 1.3 \times 10^{14}$

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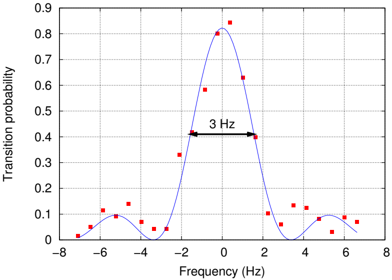

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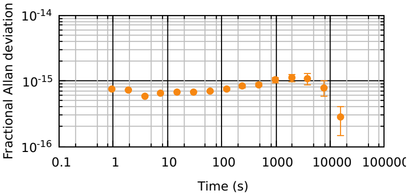
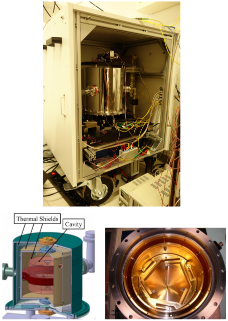
Frequency stability
Sr atoms vs. cavity



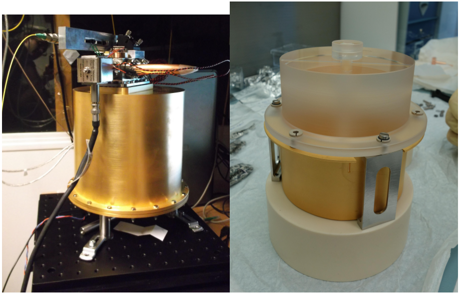
- Up to a few second: stability of the Sr clock ($10^{-15}/\sqrt{\tau}$)
- Thermal flicker noise floor at 6×10^{-15}
- Polynomial long term removed

At SYRTE – movable/transportable cavities

CUS



SOC2 cavity

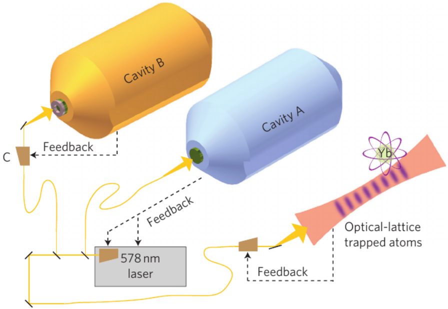


- 1.55 μm movable cavity
- Design by SODERN for CNES
- 10 cm long
- Reference for frequency combs

- Cavity for the SOC2 strontium clock laser
- 10 cm long
- 8 kg total weight

NIST, ytterbium optical lattice clock

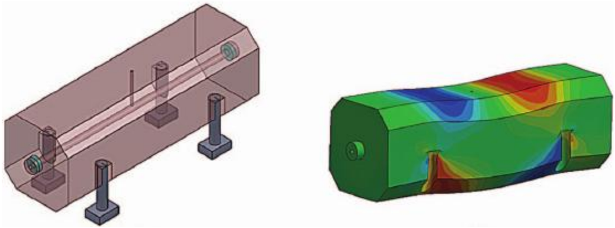
- ULE spacer, fused silica mirrors, 29 cm
- Thermal noise at 2×10^{-16} (DOI: 10.1038/nphoton.2010.313 2011)
- Comparison Yb vs Yb à $3 \times 10^{-16}/\sqrt{\tau}$ (DOI: 10.1126/science.1240420 2014)



Review of best reported stabilities – JILA

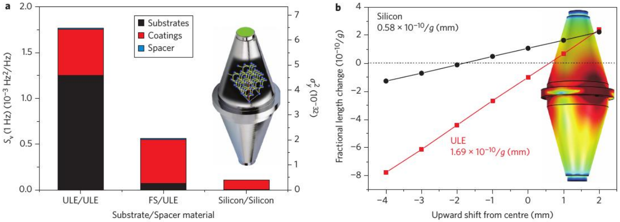
JILA, strontium optical lattice clock

- ULE spacer, fused silica mirrors, 40 cm
- Thermal noise at 1.2×10^{-16} (Phys. Rev. Lett. **109**, 230801 (2012))
- Comparaison Sr vs Sr à $2.2 \times 10^{-16}/\sqrt{\tau}$ (Nicholson, arXiv 12/2014)



PTB/JILA, Silicon cavity under liquid nitrogen

- Silicon spacer and mirrors
- Thermal noise at 7×10^{-17} (DOI 10.1038/nphoton.2012.217)
- Low long term drift at 0.1 mHz/s (DOI: 10.1364/OL.39.005102)



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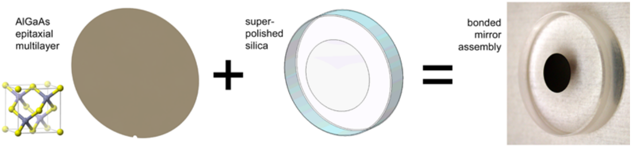
PTB, strontium optical lattice clock

- ULE spacer, fused silica mirrors, 48 cm
- Thermal noise at 8.7×10^{-17} (arXiv 1502.02608)

Projets en cours

Cavités cryogéniques avec coatings cristallins

- PTB
- JILA



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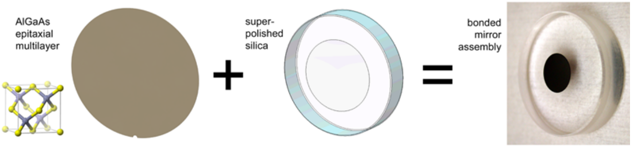

Cavités silicium cryogéniques avec cryo-cooler

- Femto-ST (Yann Kersalé, Jacques Millo)
- RIKEN (Katori)

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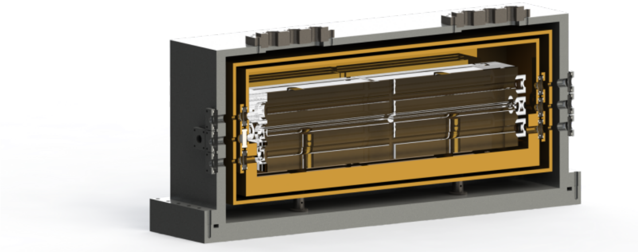
Conception



- 40 cm long cavity
- 5 optical accesses 2x 1.55 μm, 1x 1.062 μm; 1x 698 *nm* Central hole: crystalline coatings at 1.55 μm
- 2 silver-coated thermal shields

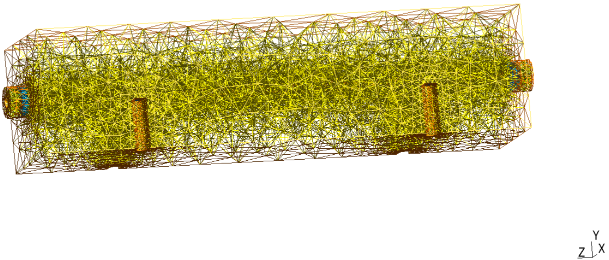
Funding

- Refimeve+
- First-TF

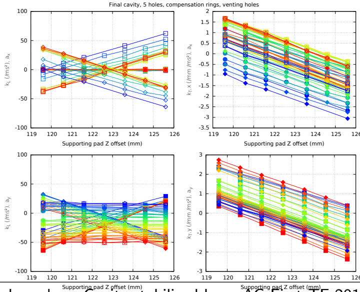
Status

- Under assembly
- Expected thermal noise floor in the 10^{-17} range

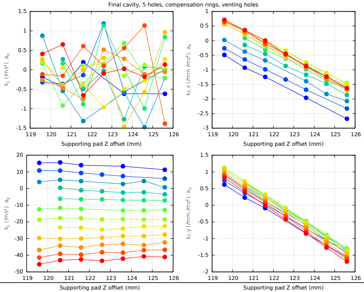
Sensibilité accélérométrique



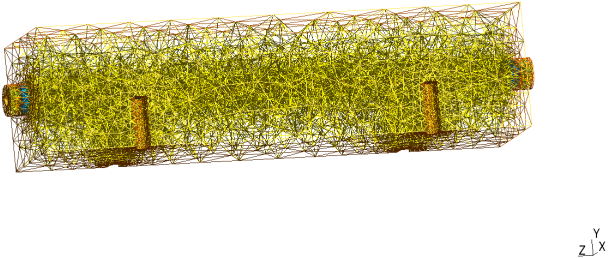
Central hole



Lateral holes



Sensibilité accélérométrique



- Sensitivity $< 10^{-11}$ /(m/s^2) on the lateral holes
  $\Rightarrow$ precision of $\sim 10\ \mu$m on the supporting points
- Tuning weights placed on the cavity for fine tuning
- Possible to reject vibration on the central hole from the signal of the lateral holes