Physics of atomic clocks

Gaetano Mileti

Laboratoire Temps – Fréquence (LTF)

(**http://www2.unine.ch/ltf**)

Institut de Microtechnique
Université de Neuchâtel

Laboratoire Temps – Fréquence (LTF)

newly created on February 1st 2007

(**http://www2.unine.ch/ltf**)

Rue A. L. Breguet 1
(c/o Institut de Physique)
Institut de Microtechnique
Université de Neuchâtel

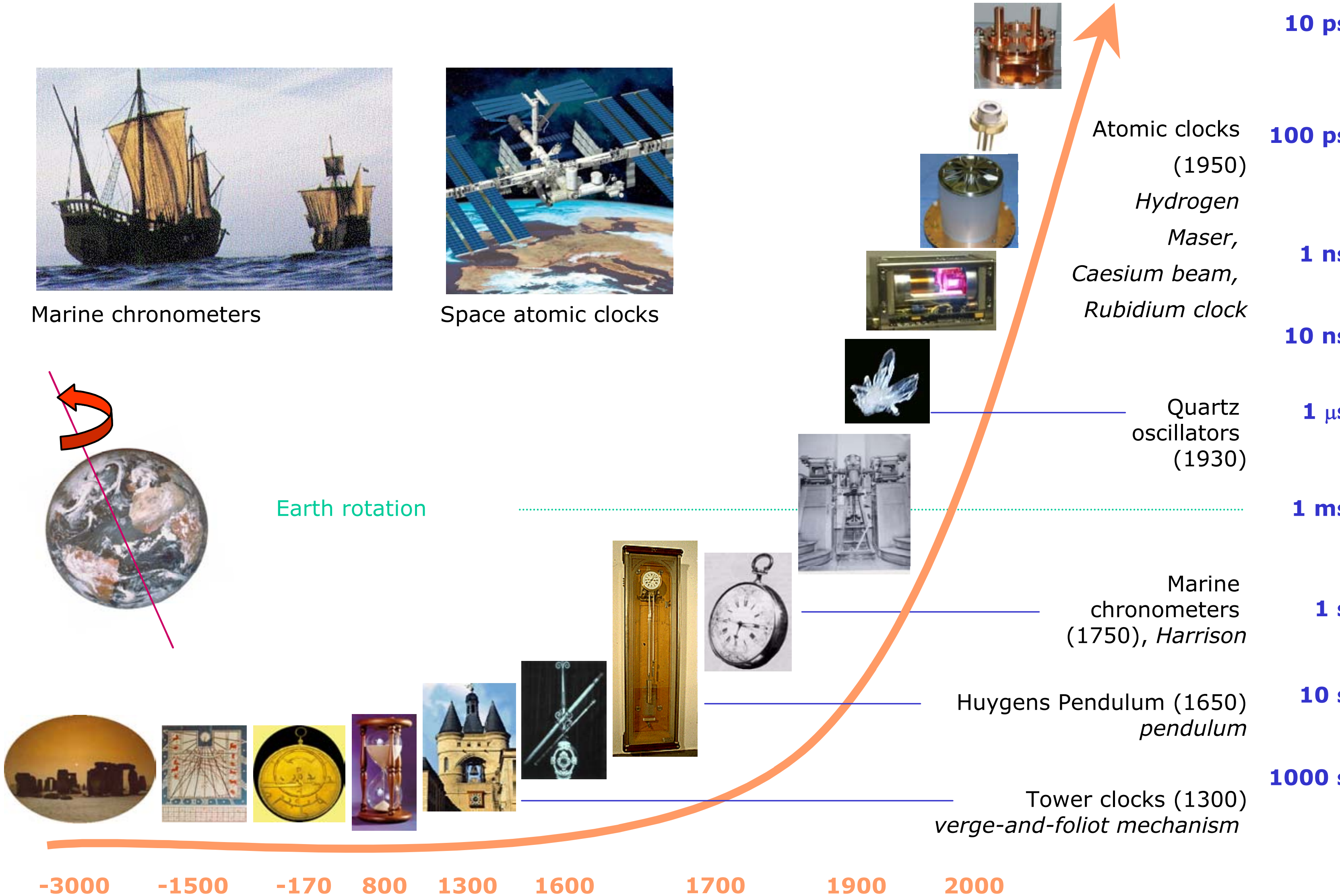
Prof. P. Thomann (Directeur du LTF)
Dr. G. Mileti (Directeur adjoint du LTF)
Dr. C. Affolderbach
Dr. C. Schori
Dr. E. Breschi
F. Füzesi
P. Scherler

Open positions: 2 postdocs, 2 pHDs

Research activities

- *Primary Cs fountains (METAS)*
- *Laser cooling*
- *Rubidium clocks*
- *Coherent Population Trapping*
- *Chip scale atomic clocks*
- *Stabilised laser diodes*
- *Optical frequency standards*

The metamorphosis of time measurement



Overview

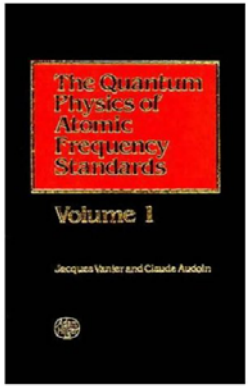
1. A few fundamentals on atomic clocks
2. Examples of atomic clock principles
3. Accuracy and stability of atomic clocks
4. New atomic clocks: exploiting laser pumping and laser cooling
5. Trends for the (near) future

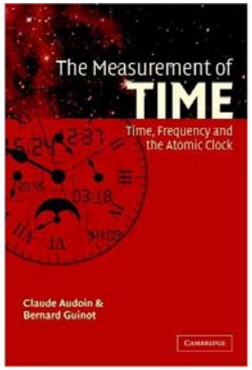
Essential Bibliography

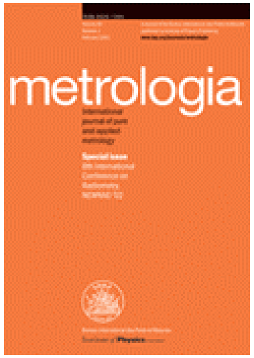
- Jacques Vanier, Claude Audoin, ***"The Quantum Physics of Atomic Frequency Standards"***, Bristol: Adam Hilger, 1989.

- Claude Audoin, Bernard Guinot, Stephen Lyle, ***"The Measurement of Time: Time, Frequency and the Atomic Clock "***, Cambridge, (Original version in french : Masson, 1998).

- Special issue of Metrologia: ***"Special issue: fifty years of atomic time-keeping: 1955 to 2005"***, *Volume 42, Number 3, June 2005.*





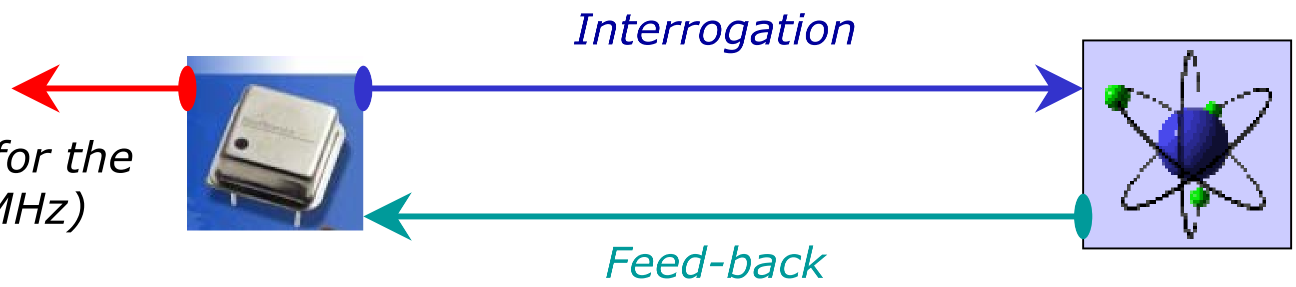


1. Fundamentals on atomic clocks

1. Basic principle of an atomic clock
2. Nuclear magnetic resonance
3. The Bloch vector
4. Advantages of atomic clocks
5. Block diagram of an atomic clock

1.1 Basic principle of an atomic clock

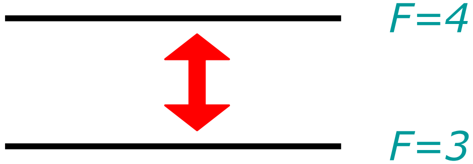
Reference for the user (5 MHz)



Quartz oscillator *Atoms*

Definition in SI system

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of cesium 133 (1967)



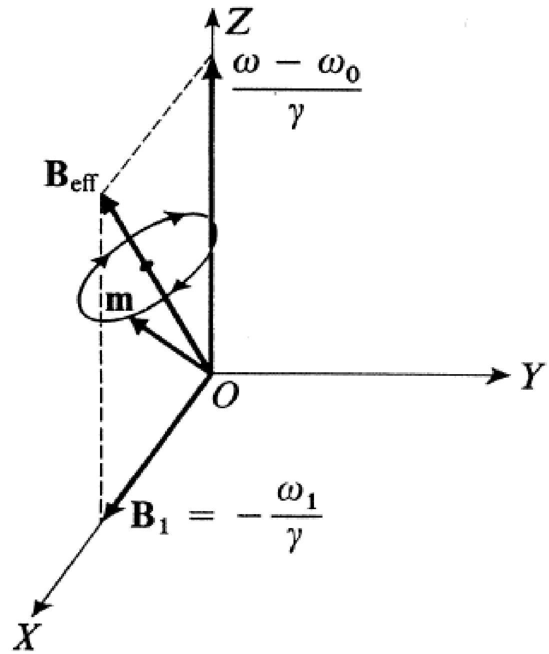
6 $S_{1/2}$

$$Frequency\ \nu_0 = \frac{E_2 - E_1}{h} = 9192\,631\,770\ Hz$$

1.2 Nuclear magnetic resonance (classical)

- Magnetic moment $\vec{m}$ interacting with a magnetic field $\vec{B}$

$$\frac{d}{dt}\vec{m}(t) = \gamma \cdot \vec{m}(t) \times \vec{B}(t)$$



- Static $\vec{B}_o$:

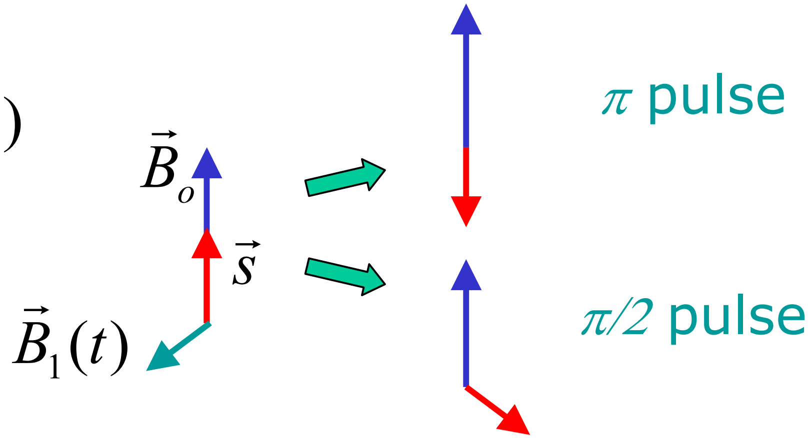
  ⇒ **Larmor precession**

$$\omega_0 = \gamma \cdot B_0$$

- $\vec{B}_o$ +rotating magnetic field $\vec{B}_1(t)$

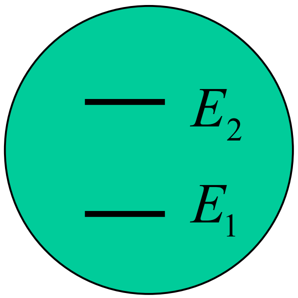
  ⇒ **magnetic resonance**

$$\omega = \omega_0$$



1.3 The Bloch vector (Quantum)

Atom (or ensemble of atoms)



Interacting field (RF, microwave, optical)

$$e^{i\omega t}$$

$$\omega \approx \frac{E_2 - E_1}{\hbar}$$

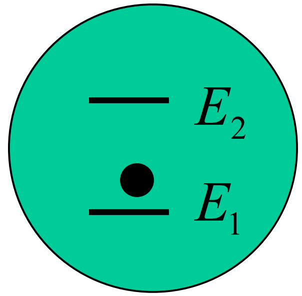
Bloch vector (fictitious spin)

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} \propto \begin{pmatrix} \textit{atomic dipole in phase} \\ \textit{atomic dipole in quadrature} \\ \textit{difference of populations} \end{pmatrix}$$

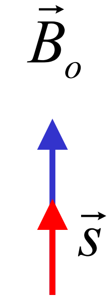
- The state of an atom (2 levels) may be represented with a vector $\vec{S}$ (“Bloch vector”, or “Fictitious spin”) and its behavior when interacting with a resonant field as a magnetic moment in a magnetic field.
- Microwave transitions, optical transitions, $\pi/2$ pulses, etc.

Examples

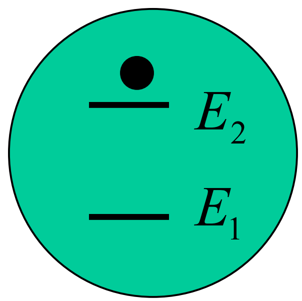
Atoms in fundamental state (no field)



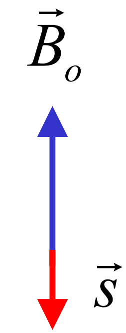
$$\vec{s} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$



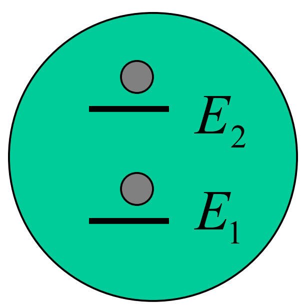
Atoms after π excitation (and field switched off)



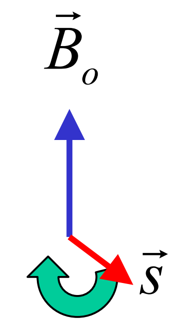
$$\vec{s} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$



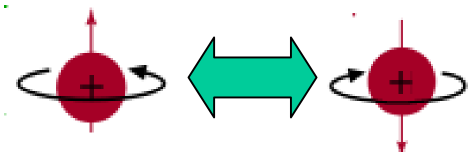
Atoms after $\pi/2$ excitation (and field switched off)
$\Rightarrow$ quantum superposition of states



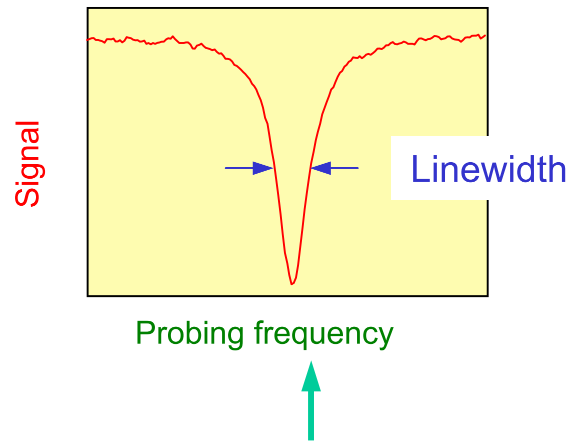
$$\vec{s} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} \cos(\omega_0 t) \\ \sin(\omega_0 t) \\ 0 \end{pmatrix}$$



***Magnetic resonance** allows spin flip.*



*It is a **frequency selective** phenomenon*



*In an **atomic clock** you exploit this phenomenon to frequency stabilise a quartz oscillator*

*In each **type of clock** it is realised on different species, in various configurations and with different detection techniques*

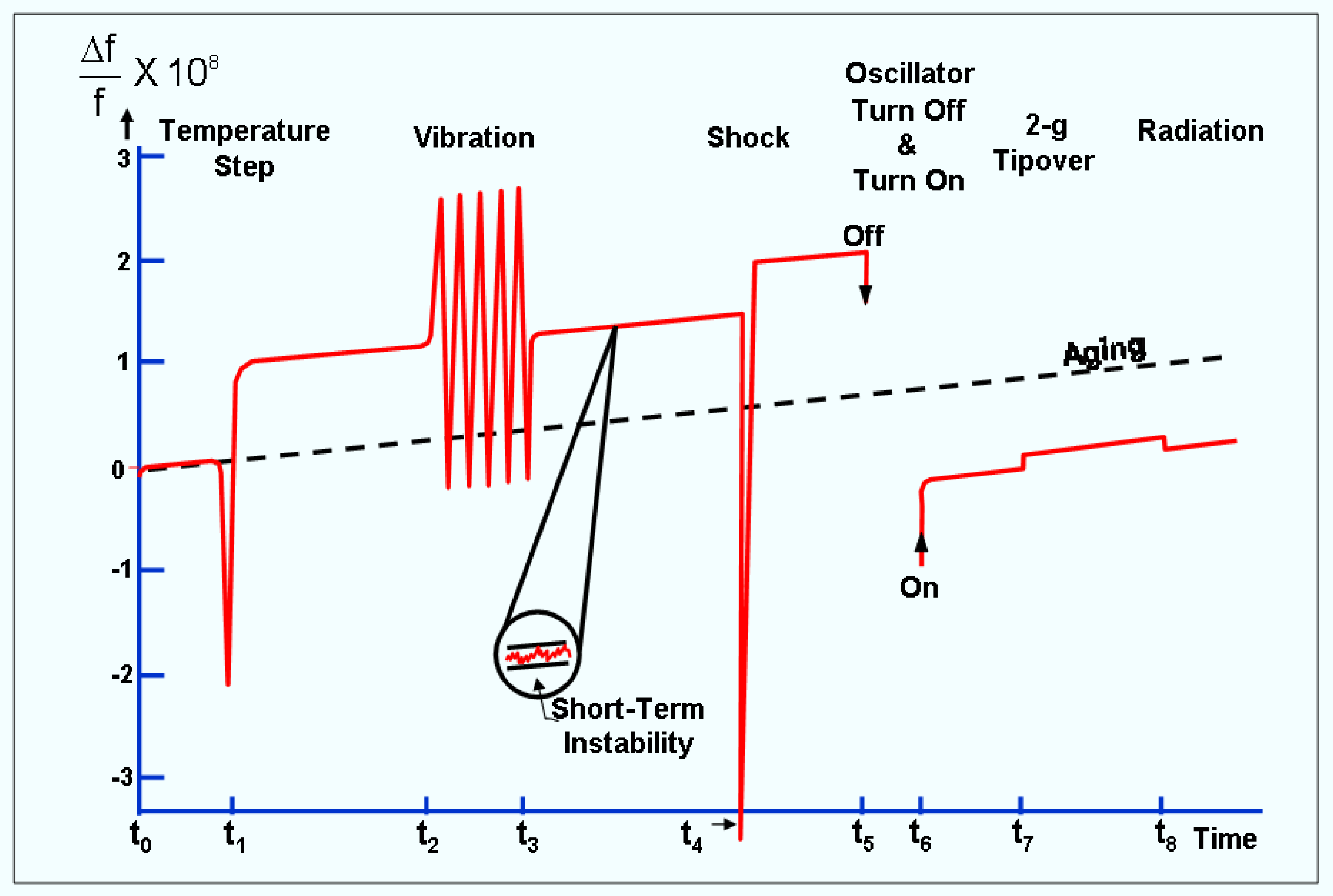
1.4 Advantages of atomic clock (over quartz)

- All (isolated) atoms of the same element and isotope have an identical structure (energy levels);
- These atoms provide a *stable* and *accurate* reference to frequency stabilize an oscillator;
- It is a fundamental and intrinsic property;
- Less sensitive to environmental effects (temperature, vibrations, etc.)
- Less aging, drift, warm-up time and retrace effect.

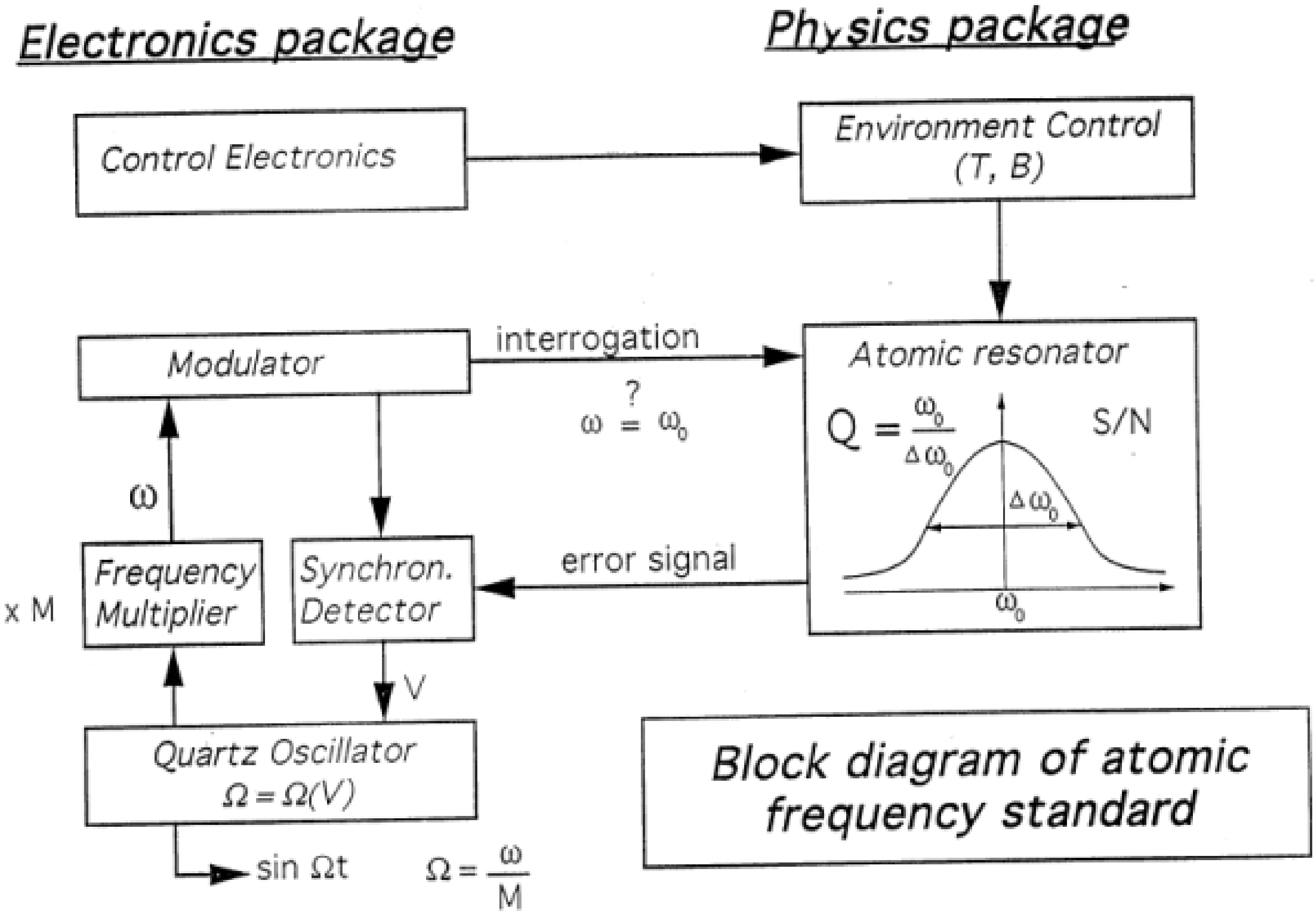
<u>But:</u>

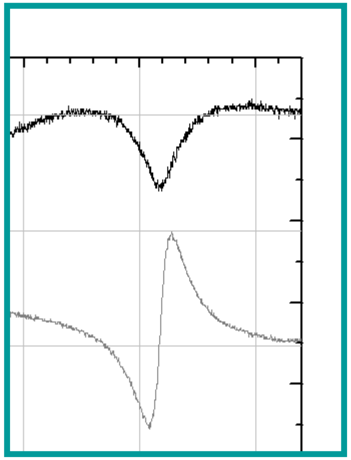
- These atoms still interact with their environment (in and out of the clock) which is responsible of the differences and drifts between the standards;
- These atoms usually move: Doppler effect, collisions, etc.

Simplified behavior of quartz oscillators



1.5 Block diagram of an atomic clock

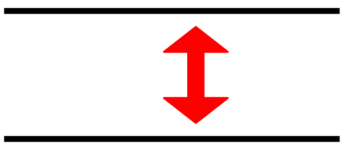




2. Examples of atomic clock principles

1. Categories and applications of atomic clocks
2. Alkali atoms in “microwave” clocks
3. Principle of thermal Cesium beams
4. Principle of Rubidium vapor cell standard
5. Other principles of atomic clocks

2.1 Categories and applications of atomic clocks (or frequency standards)



- Primary (Cs) - Secondary
- Passive – Active (H-Maser)
- Commercial (Rb, Cs, H) – Laboratory – “In development”
- Microwave - Optical

Applications of atomic clocks

- *Radioastronomy, Geodesy*

  (VLBI, Radioastron, etc.)

- *Scientific Research, Instrumentation*

  (Microgravity, ACES, HYPER, etc.)

- *Navigation & Positioning*

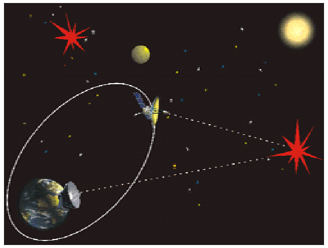
  (Galileo, GPS, GLONASS, etc.)

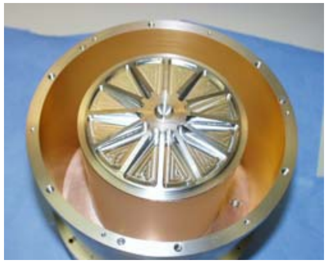
- *Telecommunications*

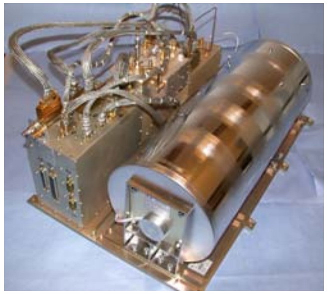
  (Networks synchronisation, etc.)

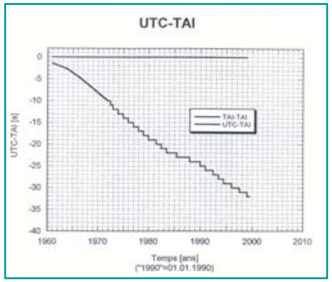
- *Metrology, Time scales*

  (Primary and secondary standards, H-Masers)





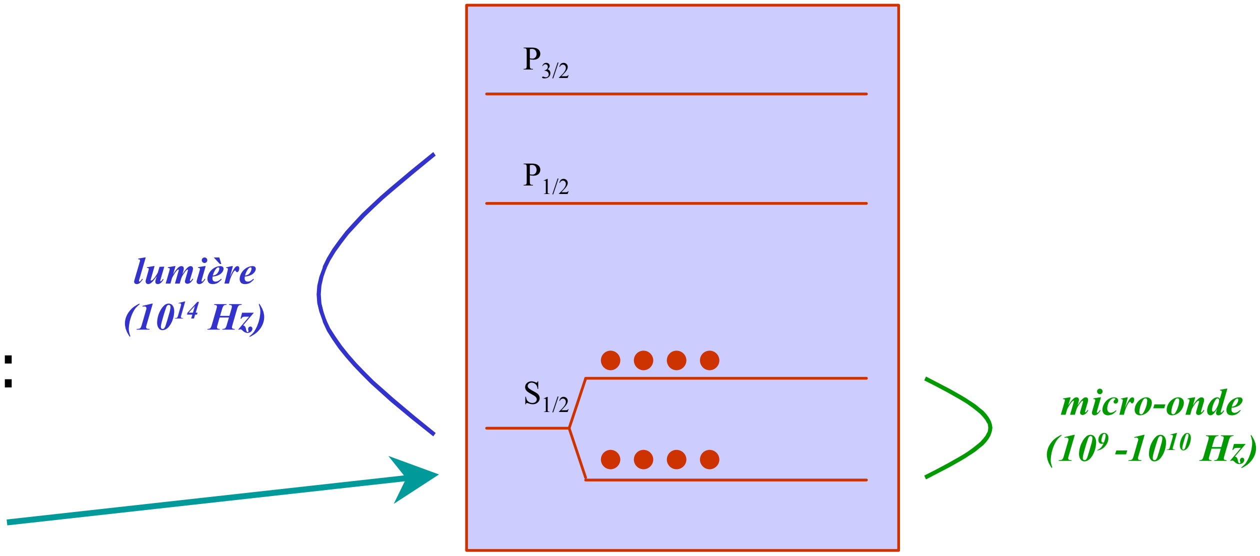


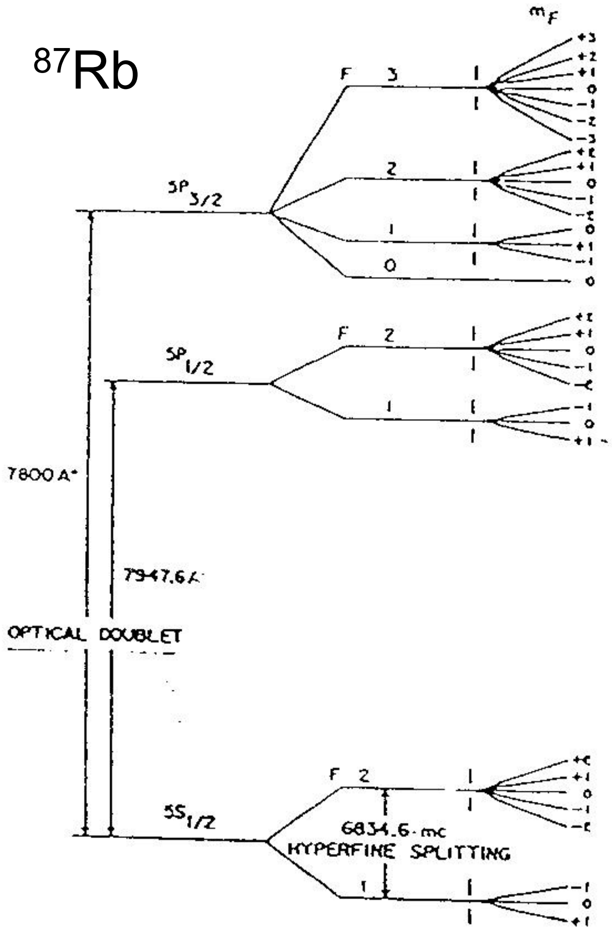


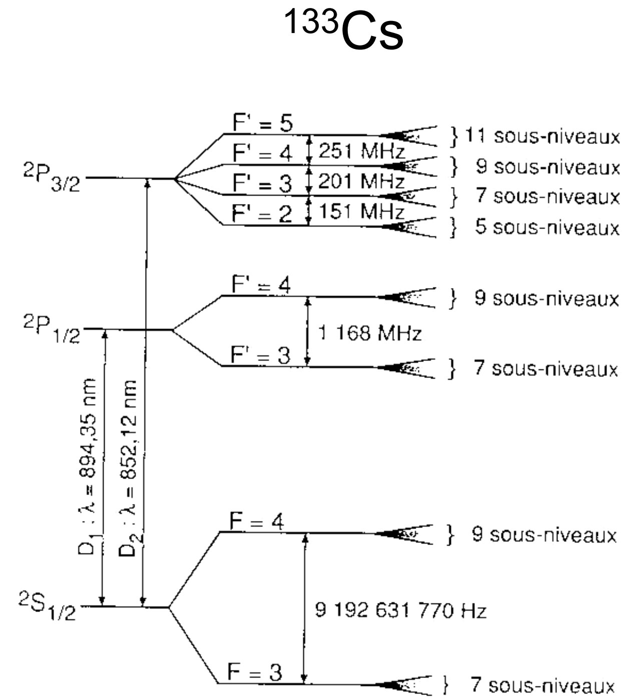
2.2 Alkali atoms in “microwave” clocks

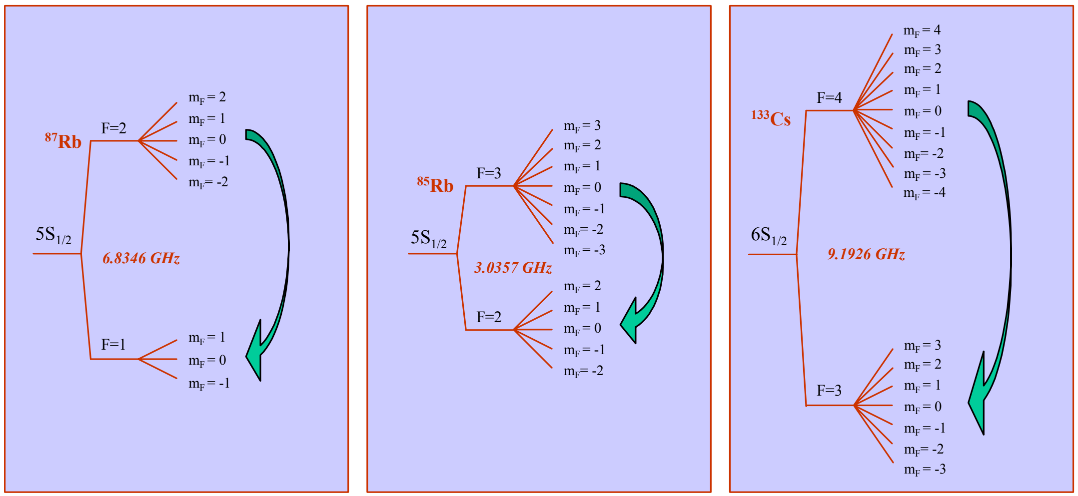
- Hydrogen-like atoms: 1 unpaired electron
- Hyperfine structure: interaction of $\vec{\mu}_e$ *with* $\vec{\mu}_{nucleous}$
- Simplified structure:
- Ground state:

$$\vec{s} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$



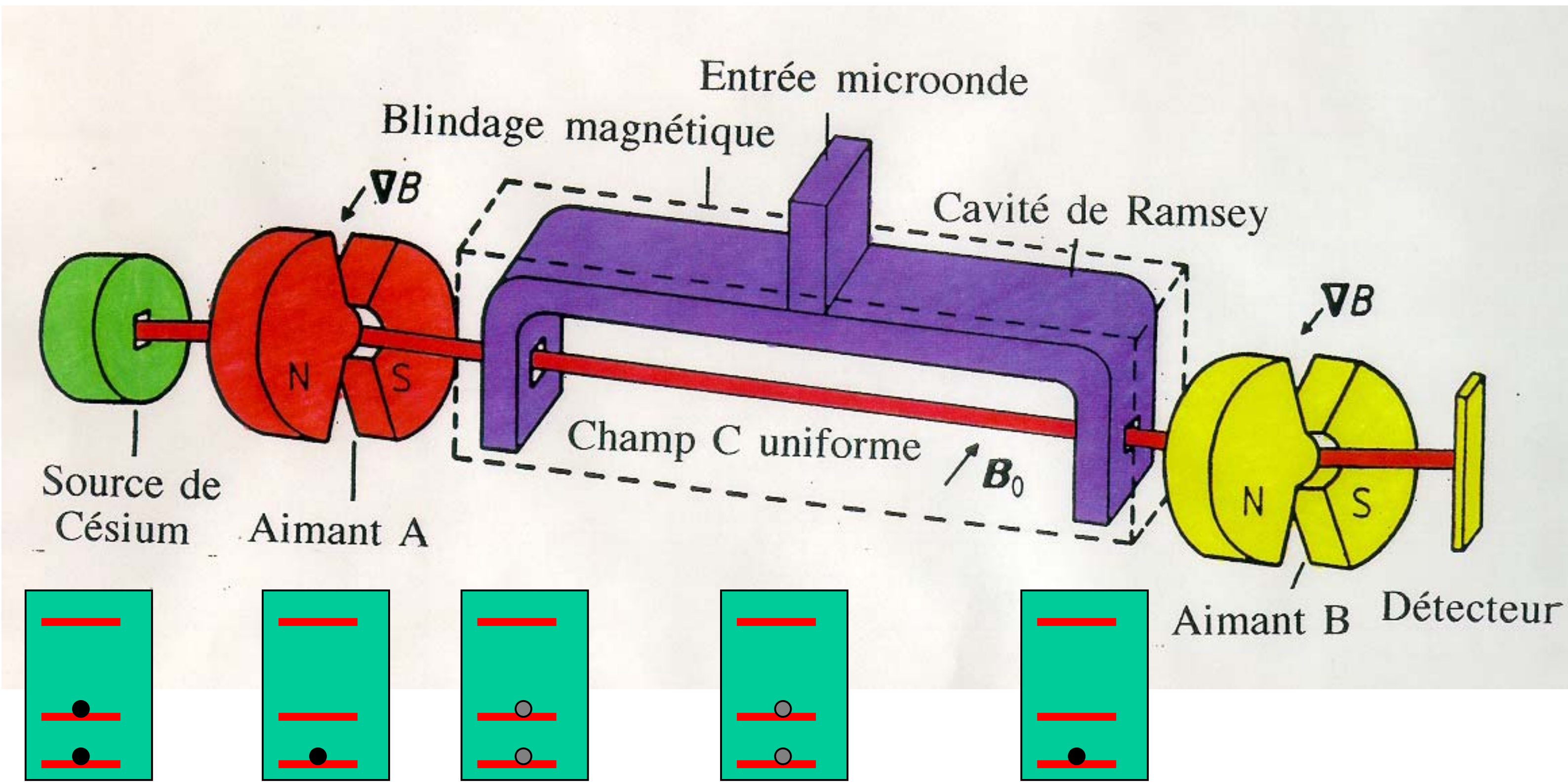

87Rb
m_F
F 3
F 2
F 1
F 0
$5P_{3/2}$
$5P_{1/2}$
$5S_{1/2}$
7800 A°
7947.6 A°
OPTICAL DOUBLET
6834.6 mc
HYPERFINE SPLITTING


133Cs
$^2P_{3/2}$
F' = 5
F' = 4
F' = 3
F' = 2
251 MHz
201 MHz
151 MHz
} 11 sous-niveaux
} 9 sous-niveaux
} 7 sous-niveaux
} 5 sous-niveaux
$^2P_{1/2}$
F' = 4
F' = 3
1 168 MHz
} 9 sous-niveaux
} 7 sous-niveaux
D_1 : λ = 894,35 nm
D_2 : λ = 852,12 nm
$^2S_{1/2}$
F = 4
F = 3
9 192 631 770 Hz
} 9 sous-niveaux
} 7 sous-niveaux

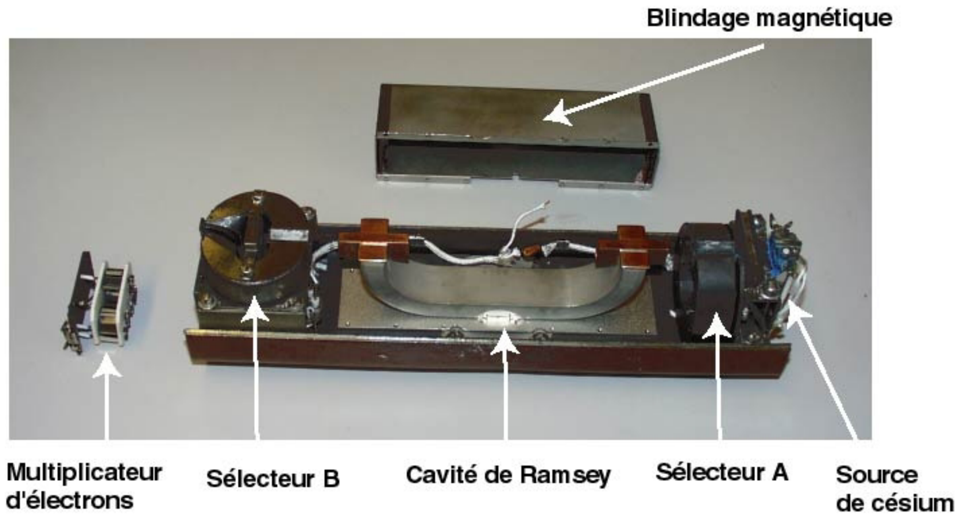

87Rb
$5S_{1/2}$
F=2
F=1
6.8346 GHz
85Rb
$5S_{1/2}$
F=3
F=2
3.0357 GHz
133Cs
$6S_{1/2}$
F=4
F=3
9.1926 GHz

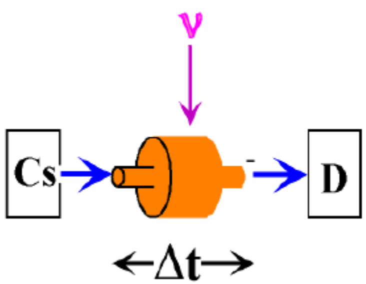
2.3 Principle of thermal Cs beams

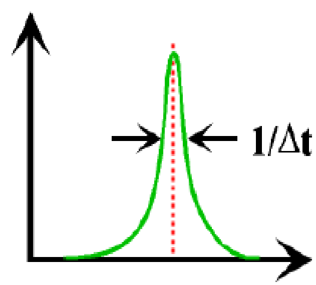
Stern-Gerlach (State selection) and Ramsey interrogation



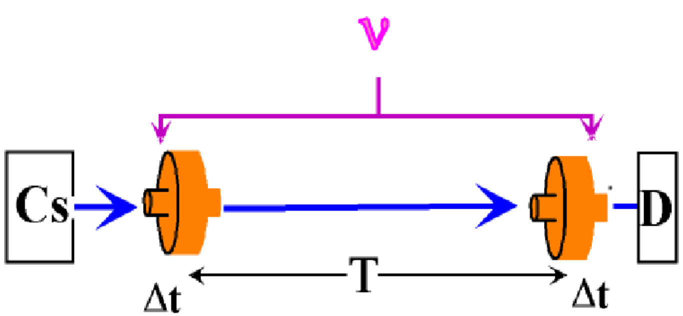
$$\vec{s} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad \begin{pmatrix} \sin(\omega_0 t) \\ \cos(\omega_0 t) \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

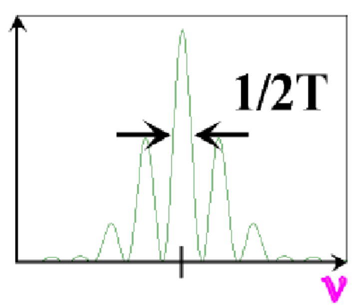


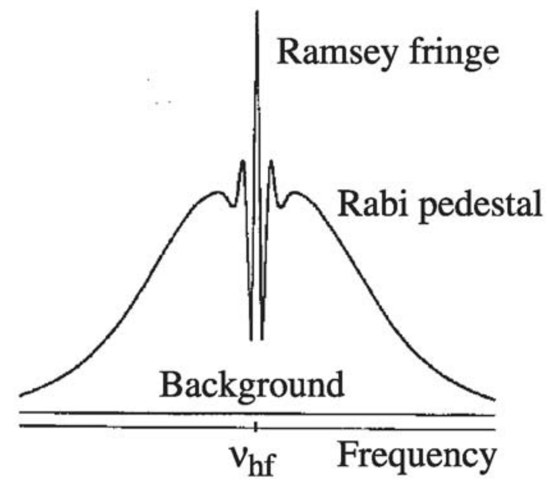




Ramsey method



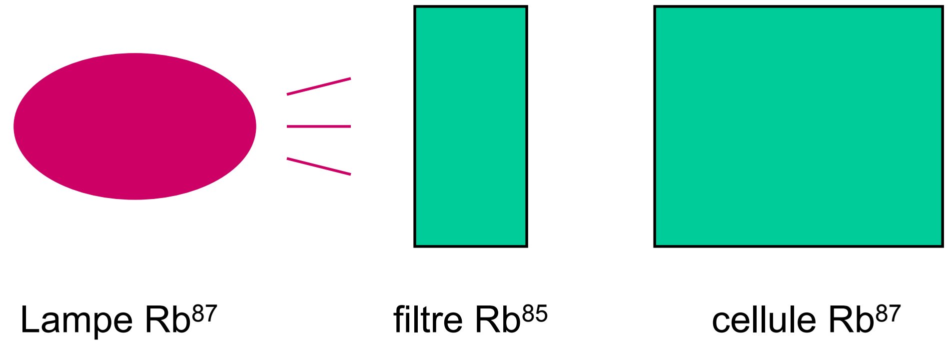


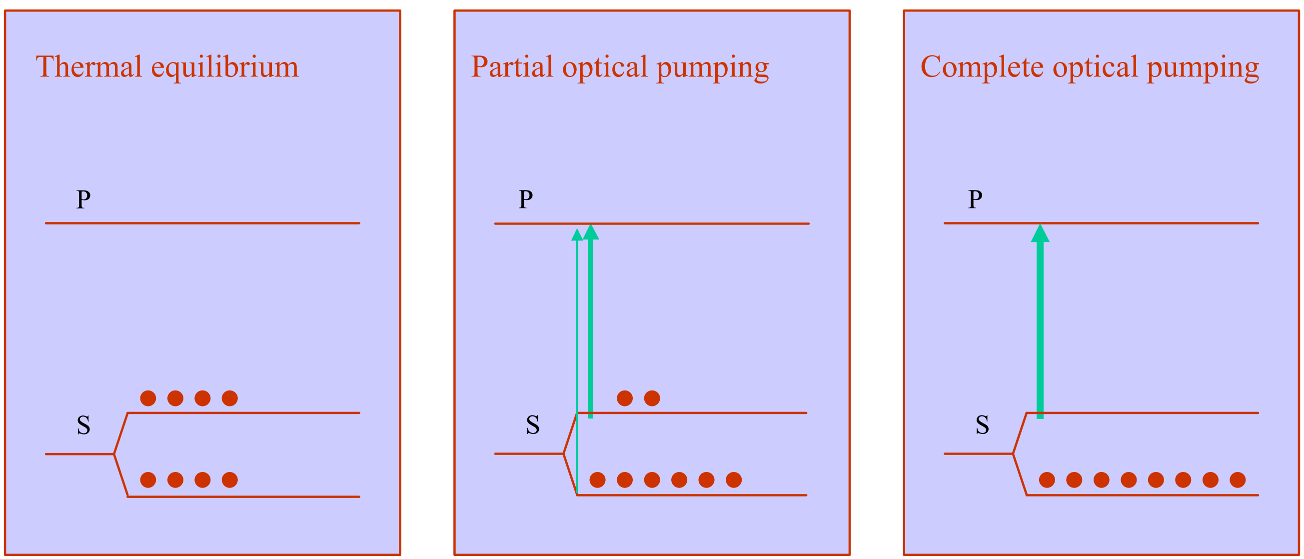


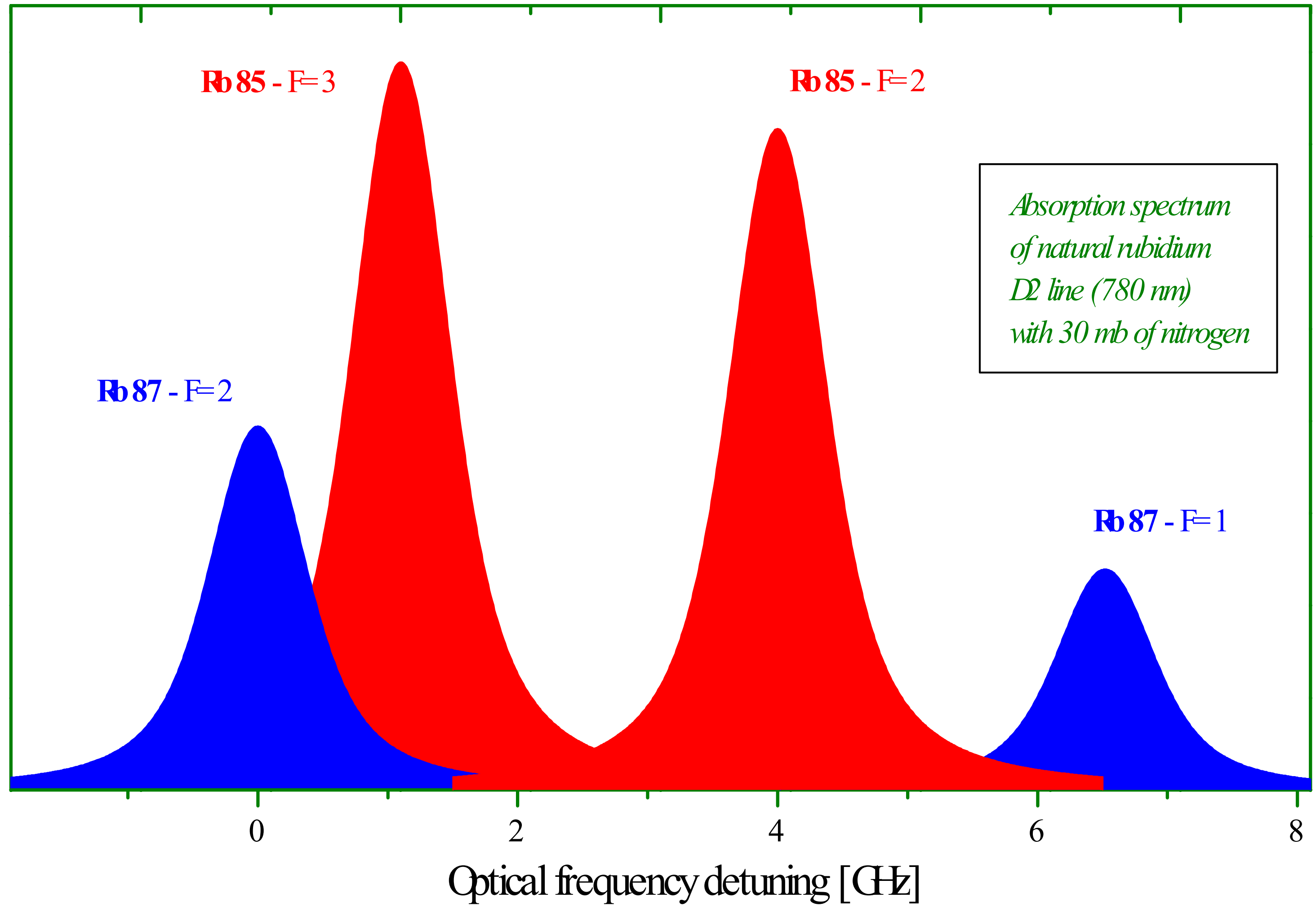
Destruction of fringes contrast due to atomic velocity distribution

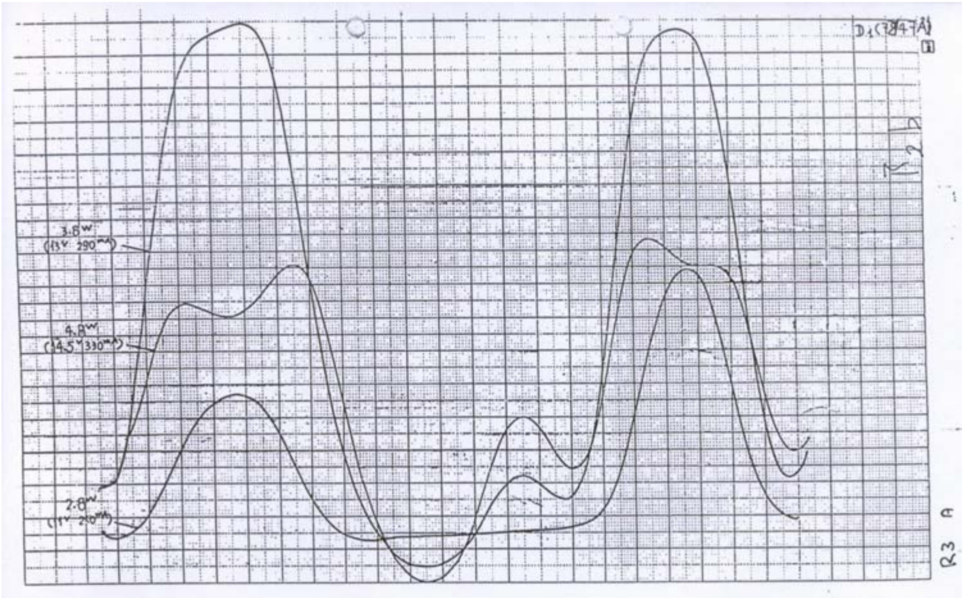
2.4 Principle of Rb cell standards

Optical pumping, Double resonance , Collisions, Light-shift

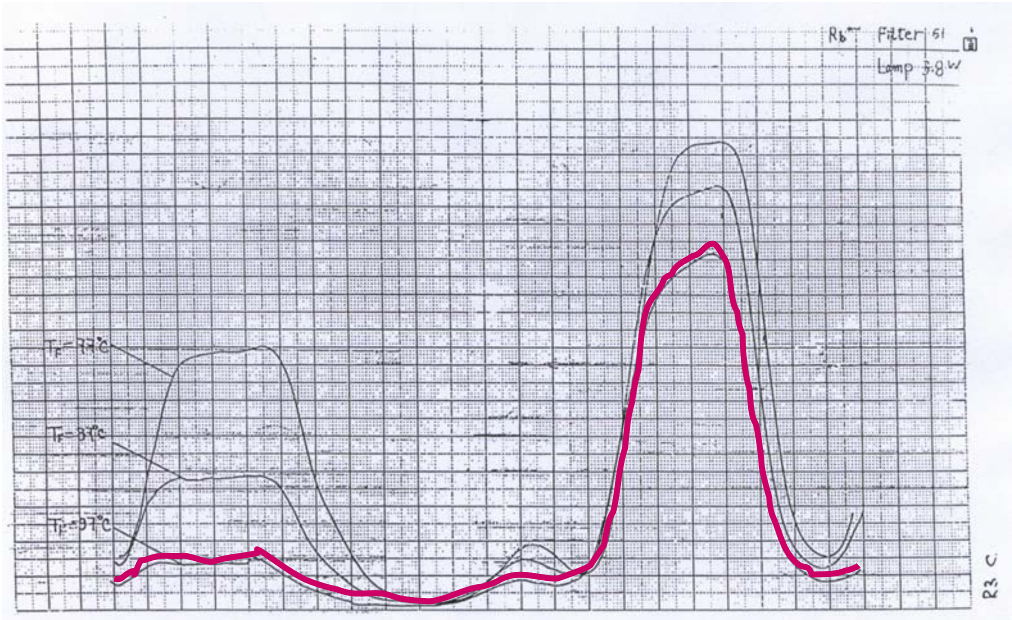





Rb 85 - F=3
Rb 85 - F=2
Absorption spectrum
of natural rubidium
D2 line (780 nm)
with 30 mb of nitrogen
Rb 87 - F=2
Rb 87 - F=1
0
2
4
6
8
Optical frequency detuning [GHz]



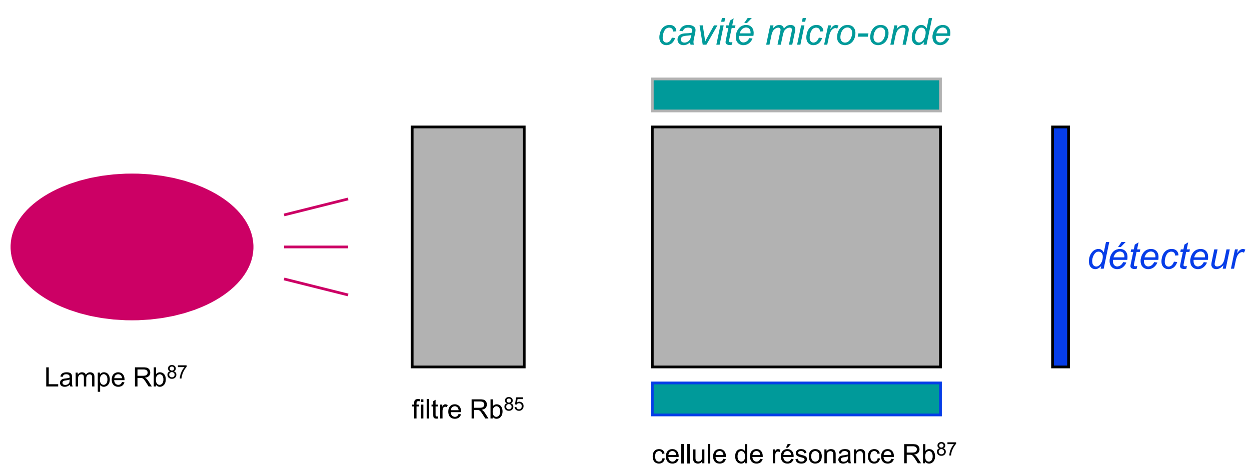
excitation d’une **lampe ^{87}Rb** avec un oscillateur RF (~120 MHz)

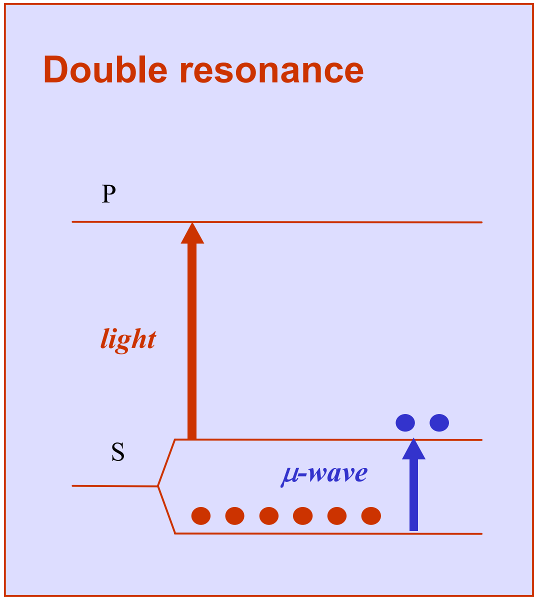


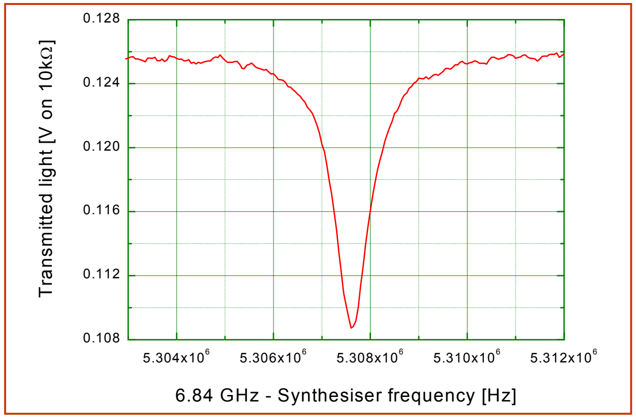
filtrage isotopique par une **cellule ^{85}Rb**

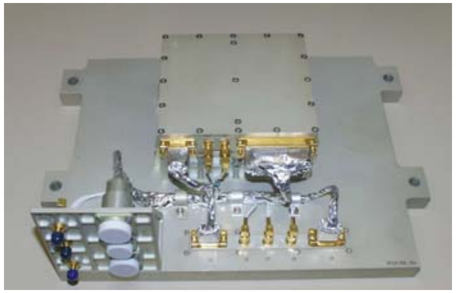
+

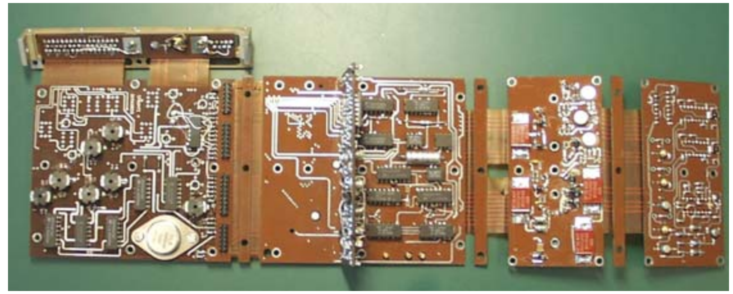
Optical pumping, Double resonance, Light-shift, Collisions

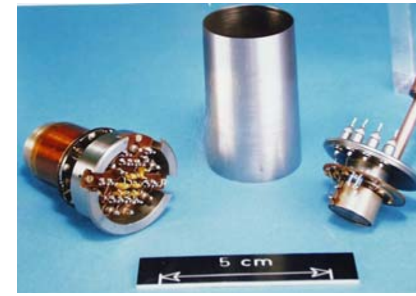


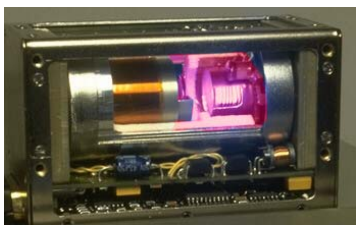


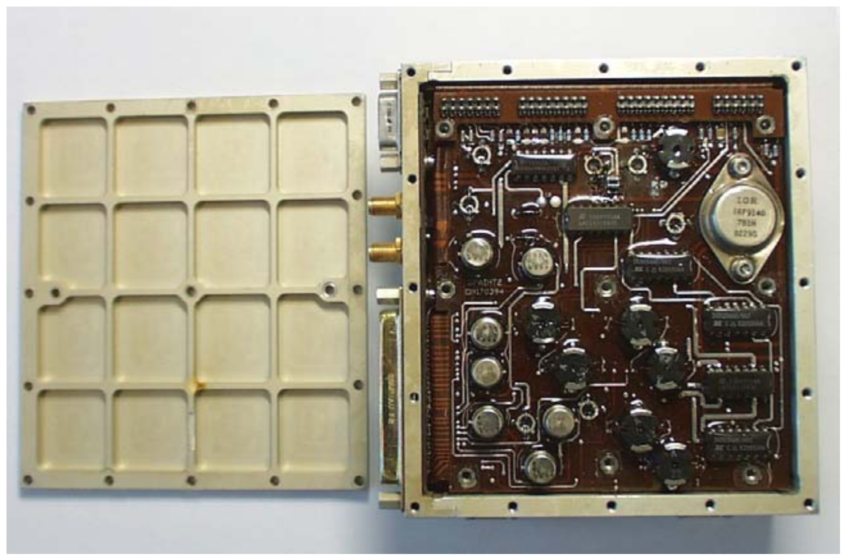


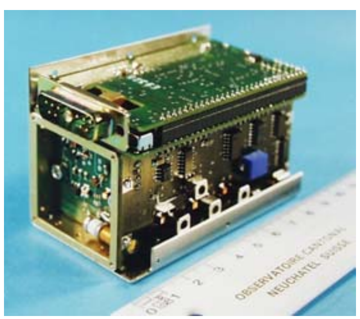





5 cm



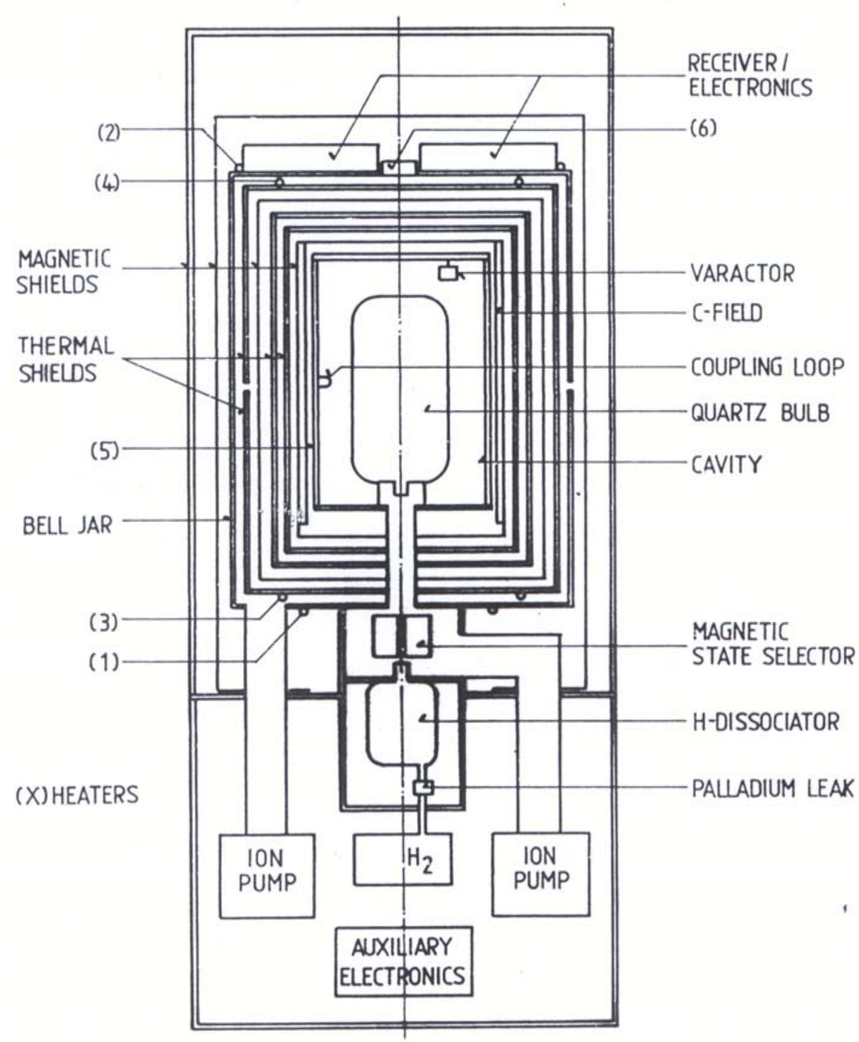



OBSERVATOIRE CANTONAL
NEUCHATEL SUISSE


5 cm

2.5 Other principles of atomic clocks (or frequency standards)

- Hydrogen Masers



- Ion traps
- Optical standards

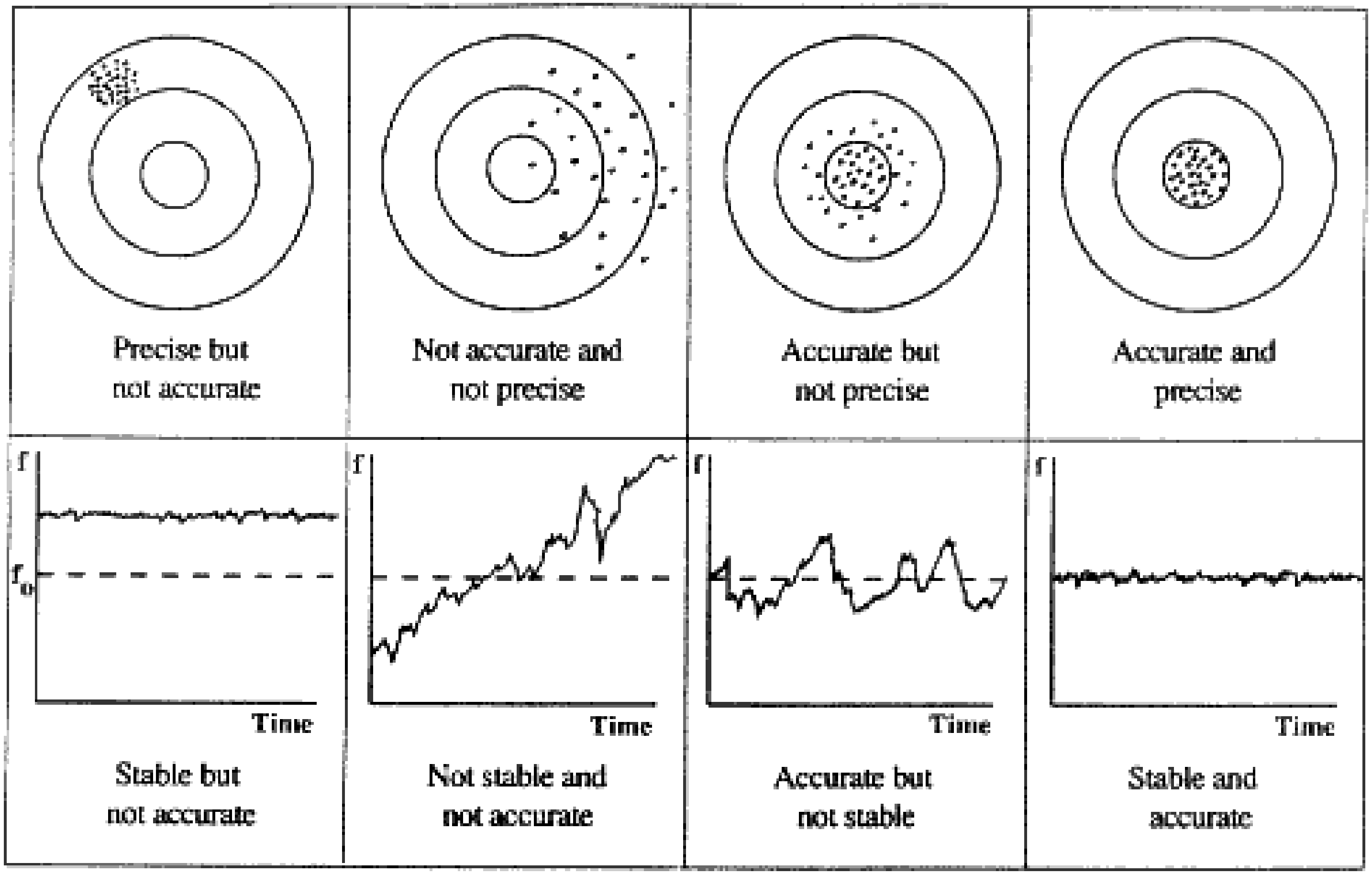
  (molecules, etc.)

  see talk of R. Holzwarth

3. Accuracy and stability of atomic clocks

1. Accuracy and stability
2. Primary frequency standards
3. Short-term frequency stability
4. Drift, aging and environmental effects
5. The role of the quartz oscillator and the LO

3.1 Accuracy and stability



3.2 Primary frequency standards

Table 4. Uncertainty budgets of the five primary clocks with a thermal beam ($\times 10^{15}$), cited in the text. '0' indicates that the component is of no relevance. It is common practice to calculate the combined uncertainty as the root-sum-of-squares of the individual components, assuming that they are linearly independent. This means that the duration of the realized second intervals agrees with the defined duration within $\pm u$ with about two-thirds probability.

Cause of frequency shift	JPO	NIST-7 (CRI-01)	NRLM-4	CS1	CS2
Quadratic Zeeman effect	1.3	1	10	1	5
Quadratic Doppler effect	2.6	3	3	1	1
AC Stark effect caused by thermal radiation	0.5	1	1	1	1
Cavity phase difference	4	4	23	6	10
Detuning of the microwave cavity	0.4	1	8	0.3	0.1
AC Stark effect caused by fluorescence radiation	2.4	1	10	0	0
Asymmetric population of the Zeeman sublevels	2.3	1	7	0.2	0.1
Electronics	2	3	1	1	3

Andreas Bauch

Meas. Sci. Technol. **14** (2003) 1159–1173

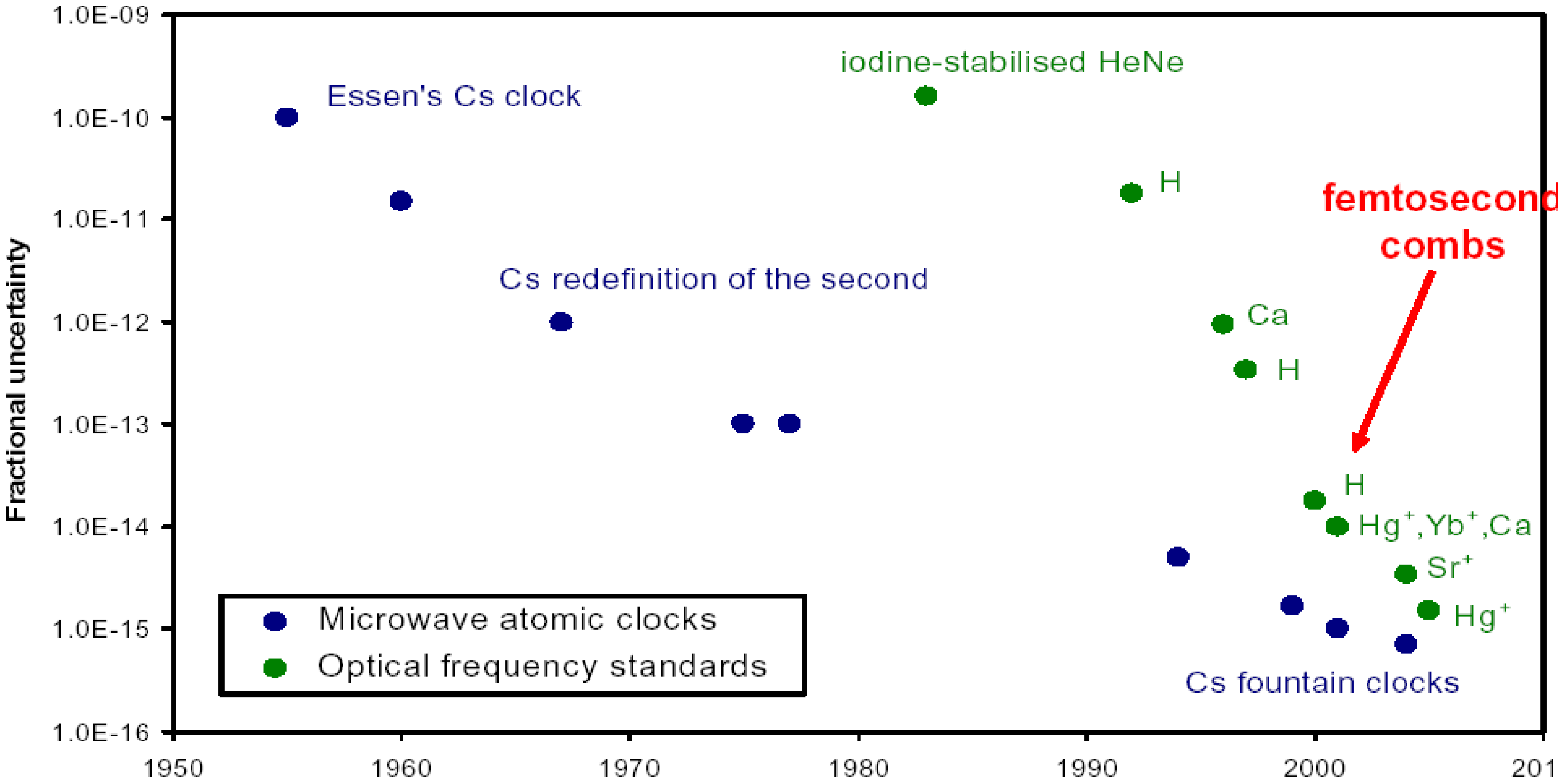
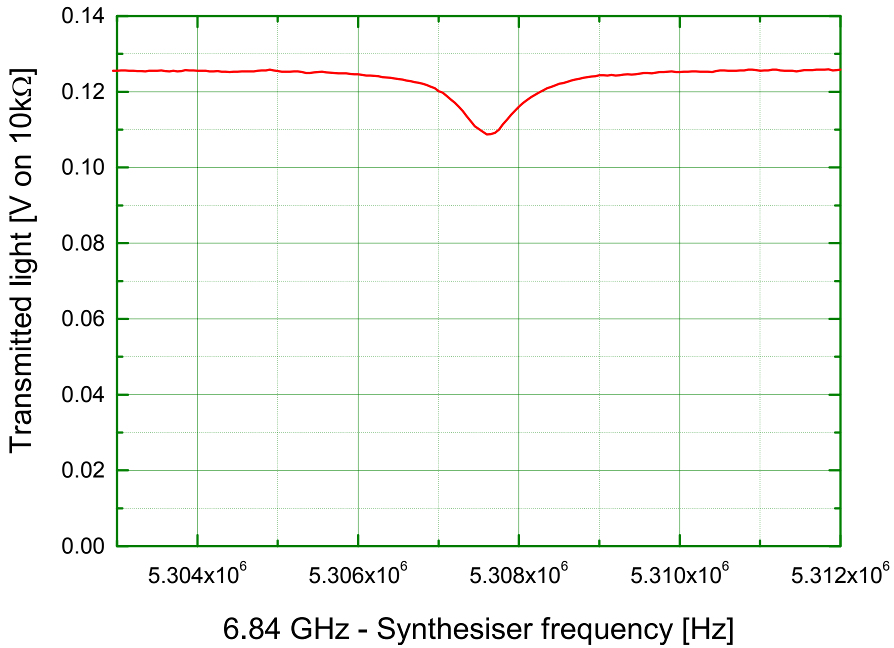


Figure: de P. Gill, «ESA Harmonisation mapping meeting», October 6 2005

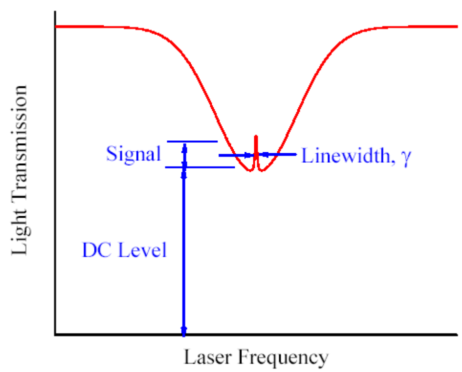
3.3 Short-term frequency stability



$$Q = \frac{\omega_0}{\Delta\omega_0}$$

$$\sigma_y^{\ I} = \frac{0.2}{Q.(S/N)} \tau^{-1/2}$$

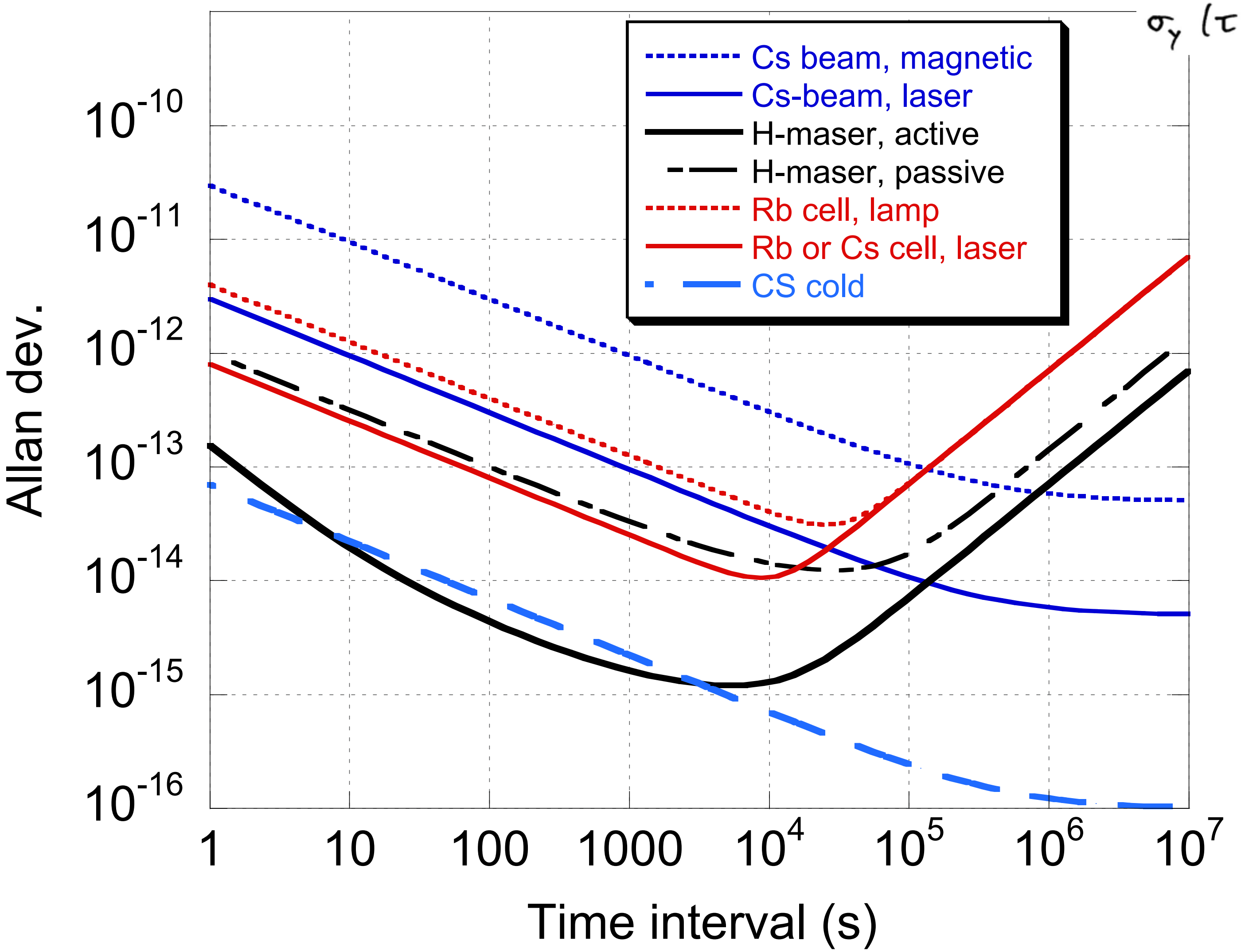
J.Vanier, L.Bernier, IEEE Trans. on Instr. and Meas., Vol. IM-30, No 4, Dec. 1981



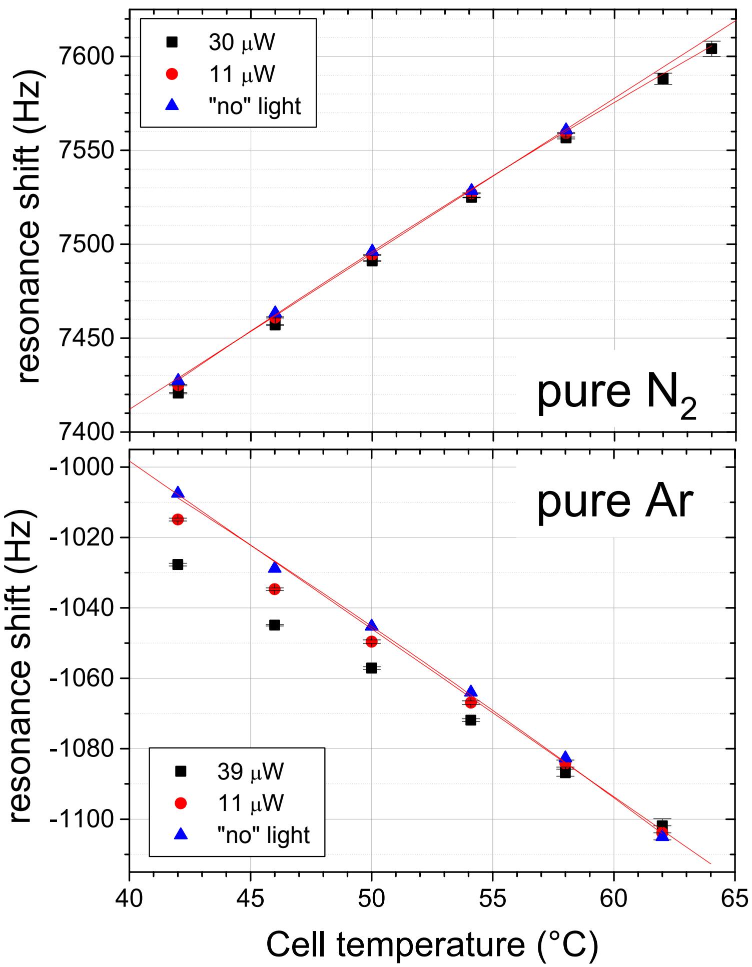
*Note: linewidth is **not** everything*

$$\sigma_y^2(\tau) = \frac{1}{2}\overline{(y_{k+1} - y_k)^2}$$

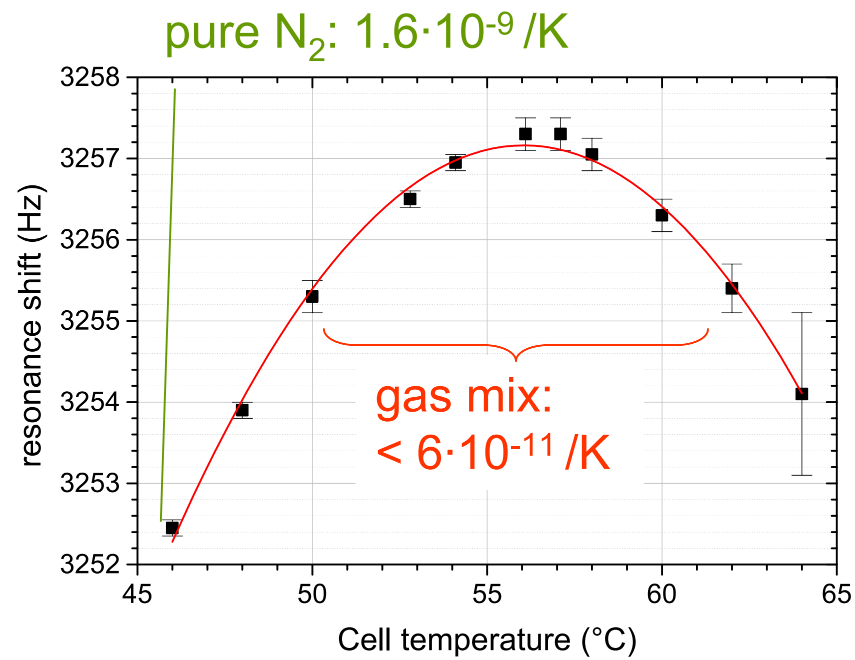
$\sigma_y(\tau) \simeq$ "déviation Allan"



3.4 Drift, aging and environmental effects



buffer-gas mixture:



long-term stability:

temperature within few mK

clock stability around 10^{-14}

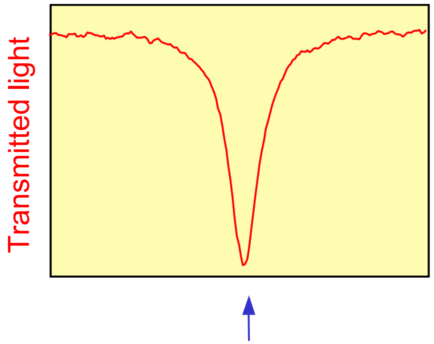
3.5 The role of the quartz oscillator and LO

LO (quartz)

- Direct AM noise and FM → AM noise

- Aliasing effects (Phase noise)

"Dick effect"



See Deng et al., PRA 59 (1) 773 (1999)

See Mileti et al., IEEE J. of Q. Electr. 34 (2) 233 (1998)

$$\sigma_y(\tau)_{PM-noise} = \sqrt{\sum_{n=1}^{\infty} C_{2n}^2 S_\phi(2nf_m)} \cdot \tau^{-1/2}$$

Finally:

$$\left(\sigma_y^{total}(\tau)\right)^2 \approx \left(\sigma_y^{I noise}(\tau)\right)^2 + \left(\sigma_y^{PM noise}(\tau)\right)^2 + \left(\sigma_y^{ls}(\tau)\right)^2$$

4. New atomic clocks: exploiting laser pumping and laser cooling

1. Tunable diode lasers
2. Optically-pumped thermal Cesium beam
3. Laser-pumped vapour cell standard
4. Coherent Population Trapping (CPT)
5. Cold atoms clocks
6. Other standards using diode lasers

4.1 Tuneable diode lasers

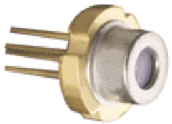
Potential advantages of using diode lasers:

- More efficient atomic state preparation / selection:

  Examples: optical pumping in Rb, Cs, Maser

- Improved detection of atomic states (S/N):

  Examples: optical pumping in Rb, Cs, Maser



- Possibility to slow (cool) or trap atoms

  Examples: cold atoms frequency standards

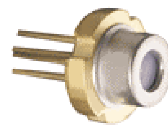
- Explore new physical phenomena

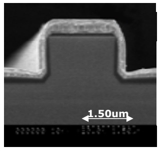
  Examples: Coherent Population Trapping

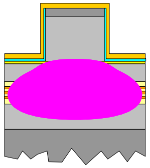
- Miniaturization, etc.

Open issues: availability, reliability, cost, etc.

Examples of Laser diodes

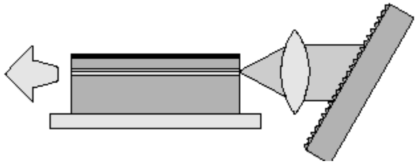




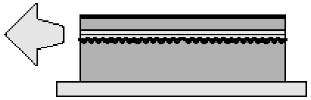


FP (RWL)

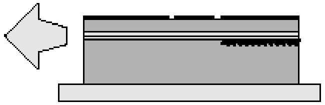
- Solitary Fabry-Perot (FP)
- Extended cavity lasers (ECDL)
- Distributed Bragg Reflectors (DBR)
- Distributed Feedback (DFB)
- FP with DBR optical fiber
- Vertical Cavity Surface Emitting (VCSEL)
- MEMS based ECDL and VCSEL
- Etc.



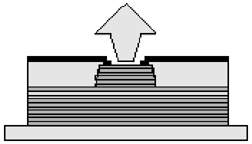
ECDL



DFB

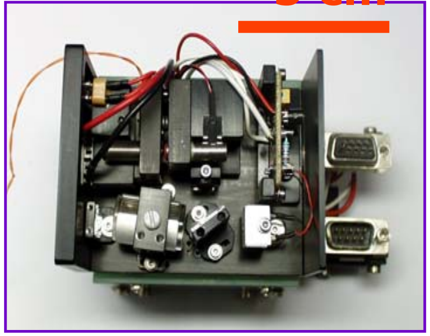


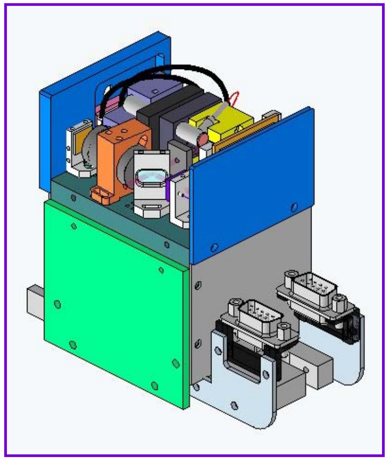
DBR



VCSEL

5 cm

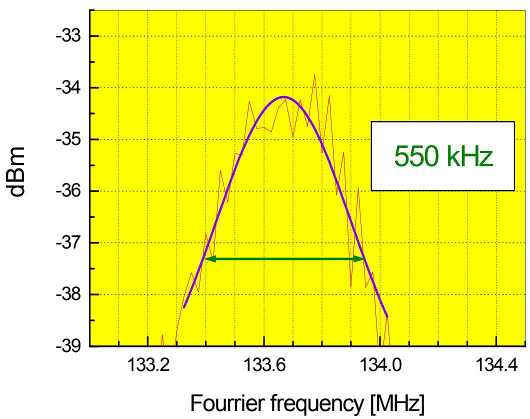




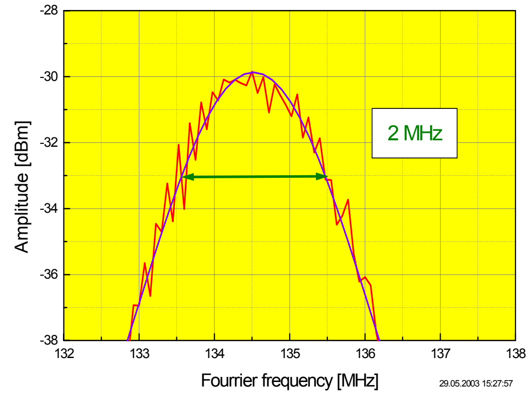
Laser spectral cacterisation

***Example 1**: heterodyne frequency spectrum*

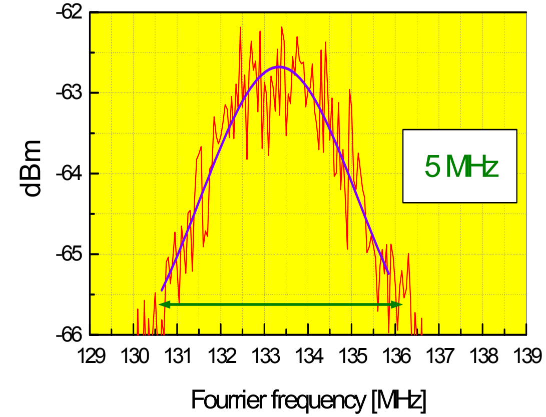
Laboratory ECDL vs ***Laboratory ECDL***



ESA-ECDL vs ***DBR***

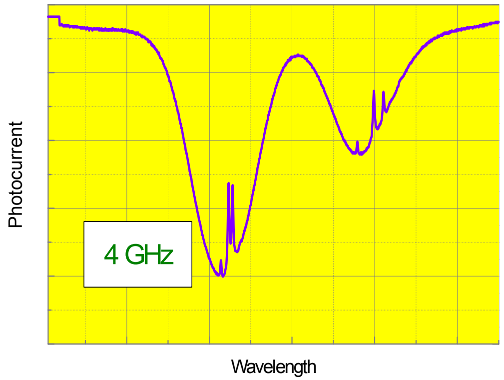


ESA-ECDL vs ***DFB***

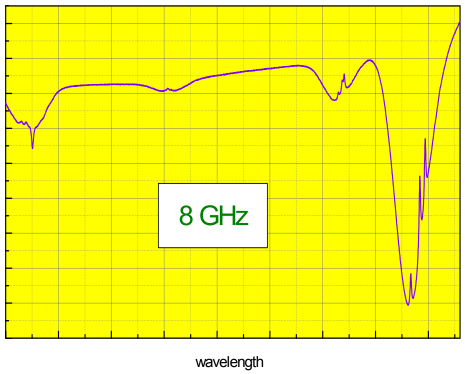


***Example 2**: mode-hope free tuning range*

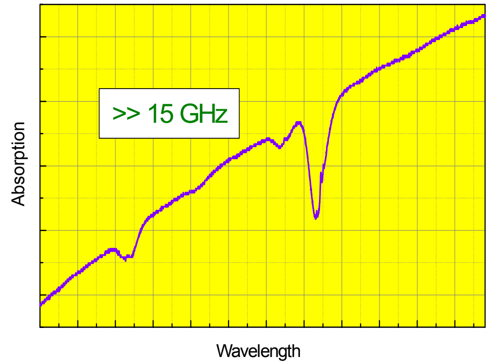
Laboratory ECDL



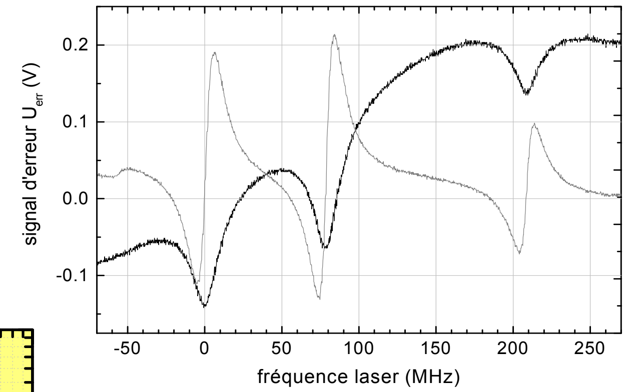
DBR

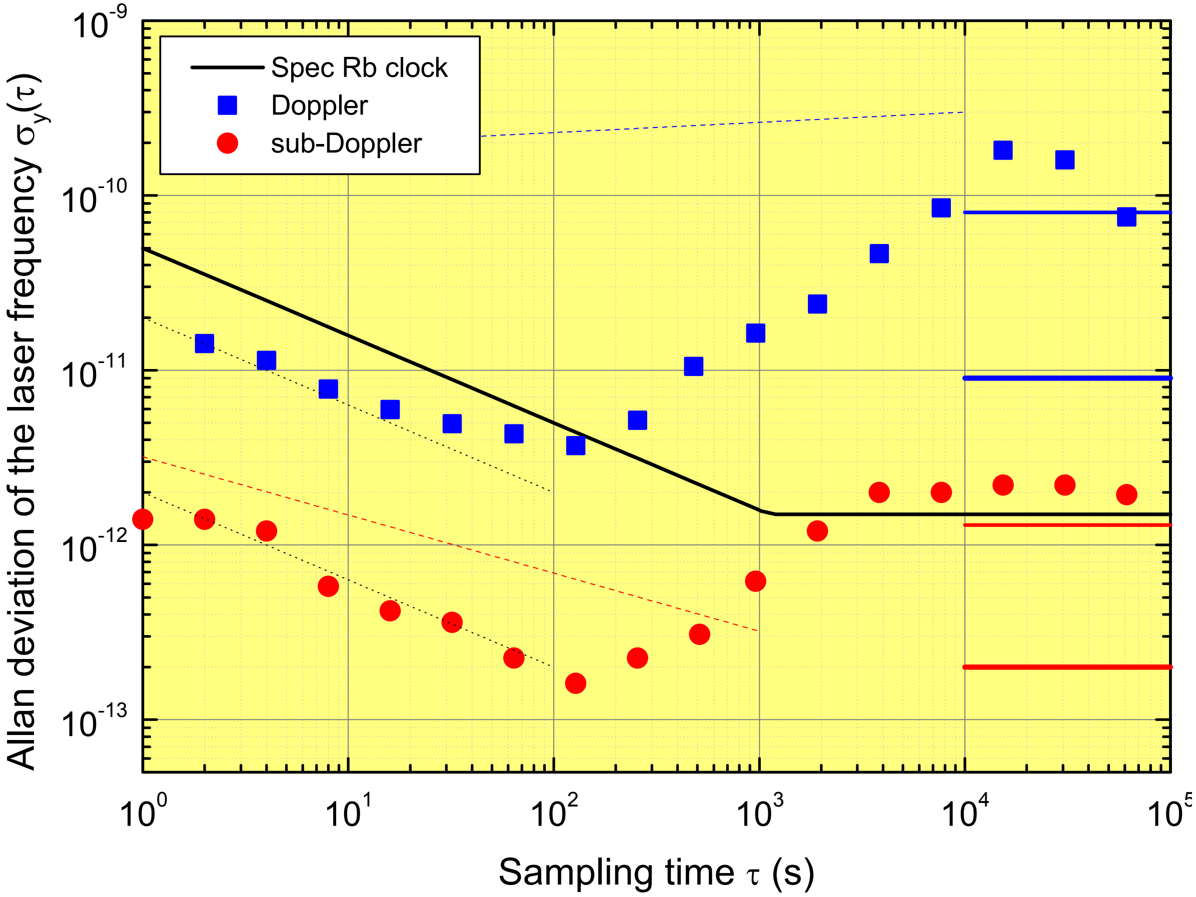


DFB

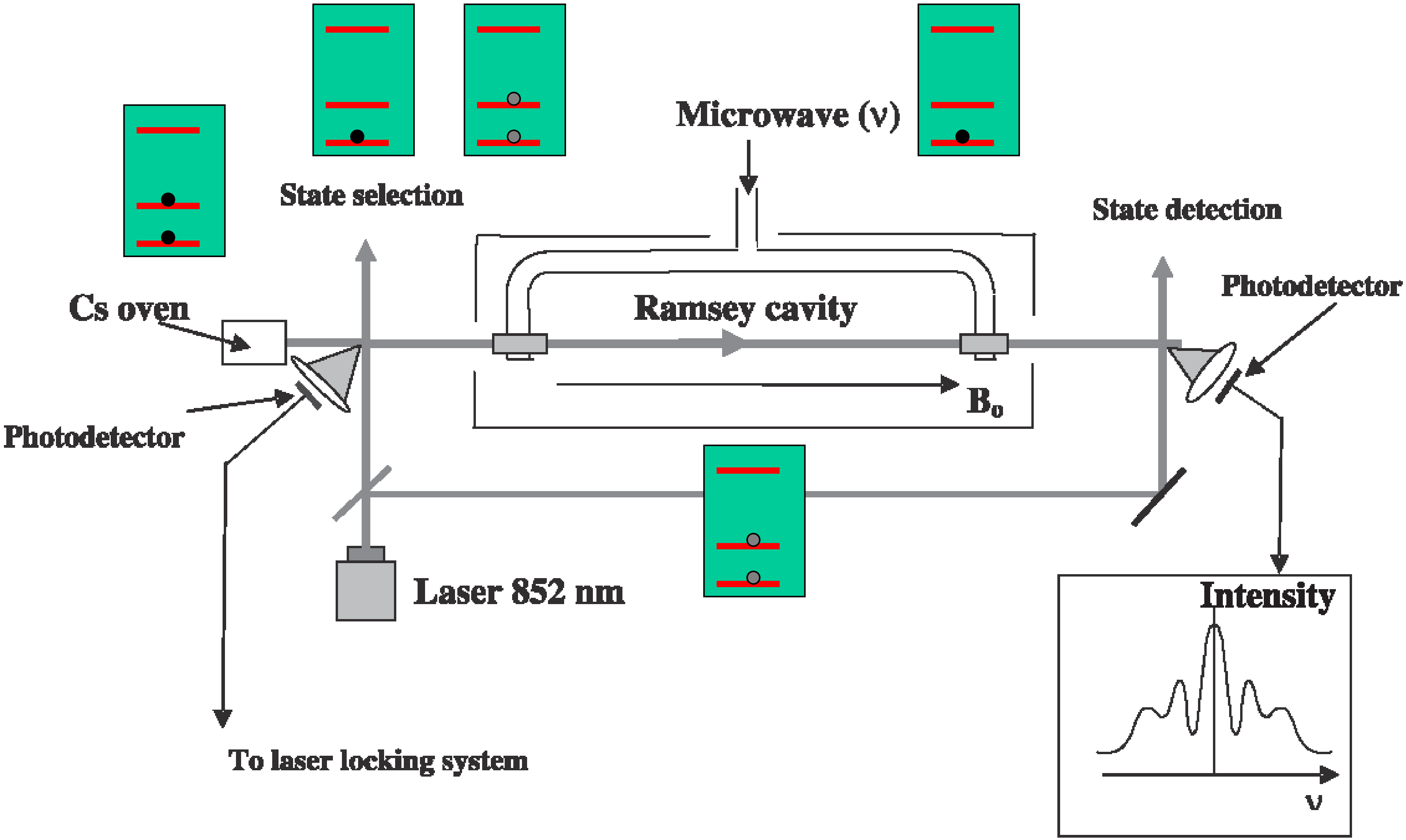


Laser frequency stabilisation

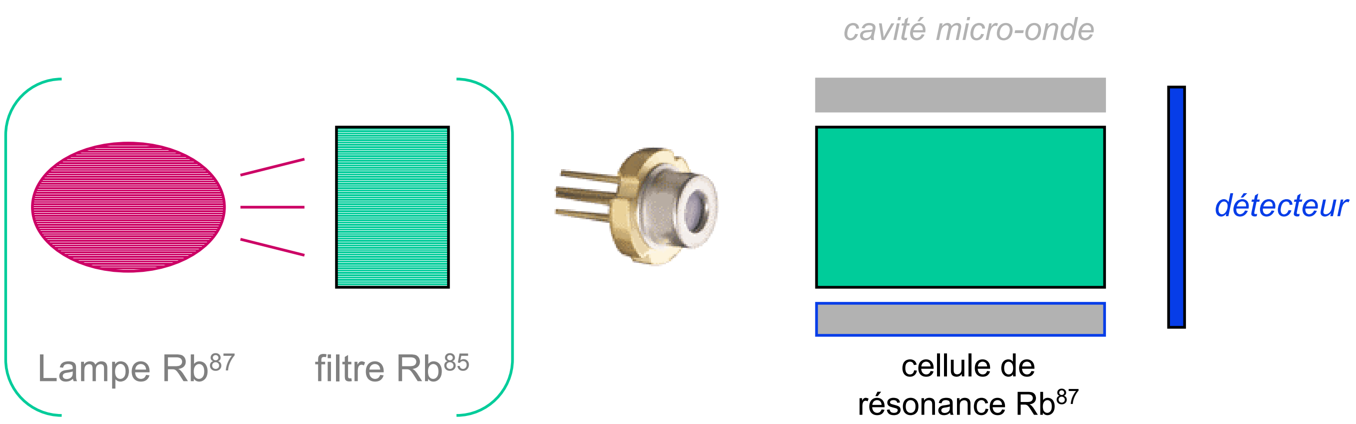




4.2 Optically-pumped thermal Cs beam

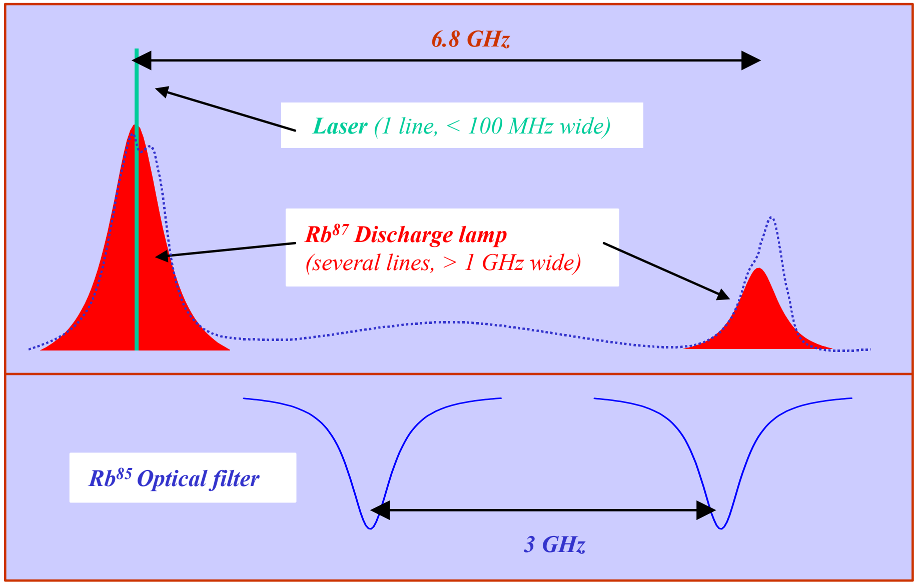


4.3 Laser-pumped vapour cell standard



Potential advantages:

- More efficient pumping
- Improved S/N
- Long term stability
- Power / Weight / Volume
- Redundancy

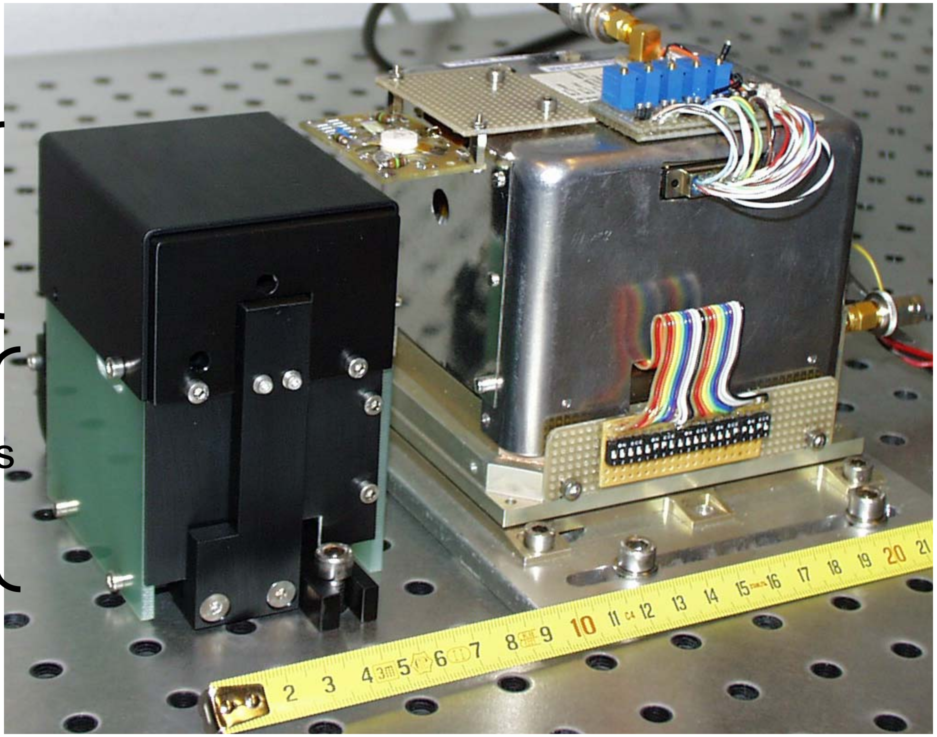


Laser-pumped Rb prototype

ESA-funded project

Physics package *(200cm³)*

Volume for control electronics *(300cm³, currently empty)*



Stabilised laser head:

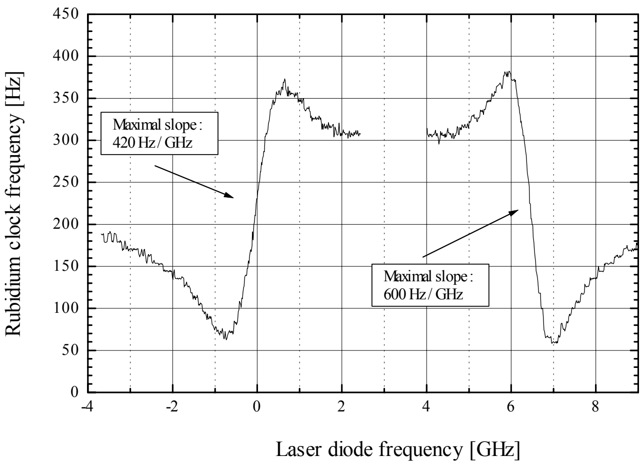
RAFS resonator module:

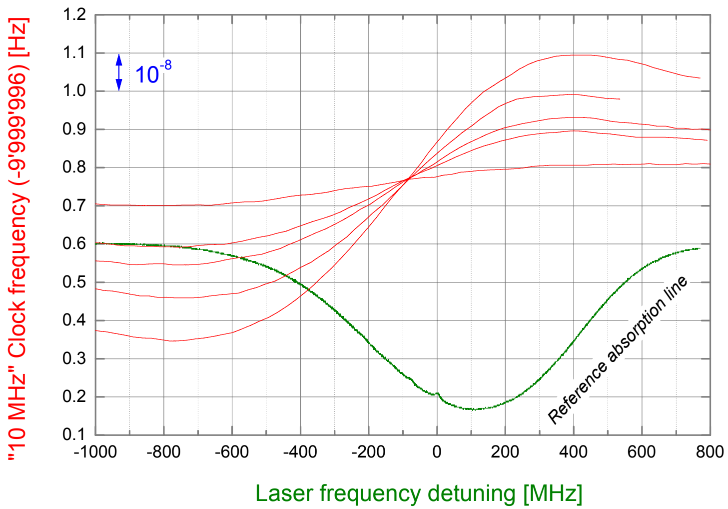
- adapted resonance cell,
- lamp removed,

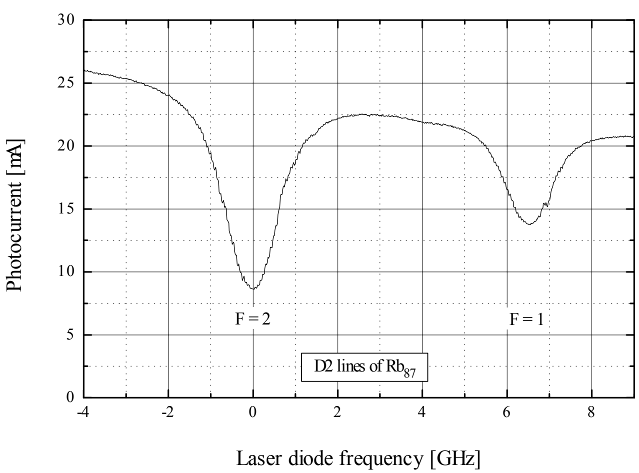
(empty volume!)

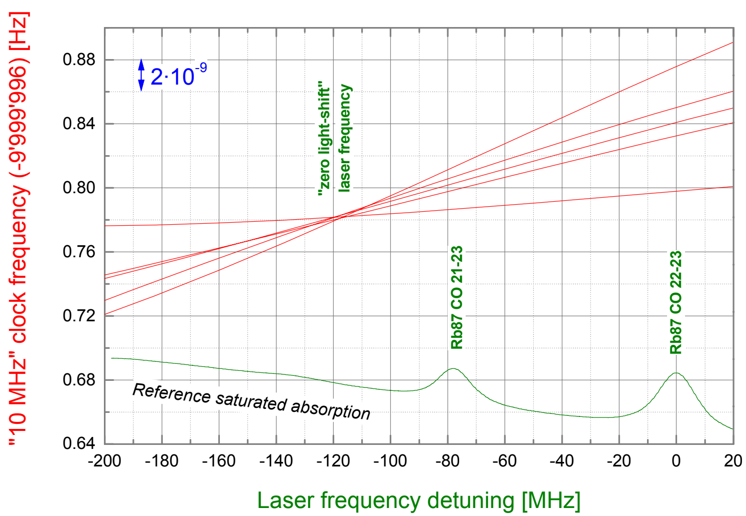
Light-shift

Shift of the resonance frequency induced by the optical radiation (I, ν)

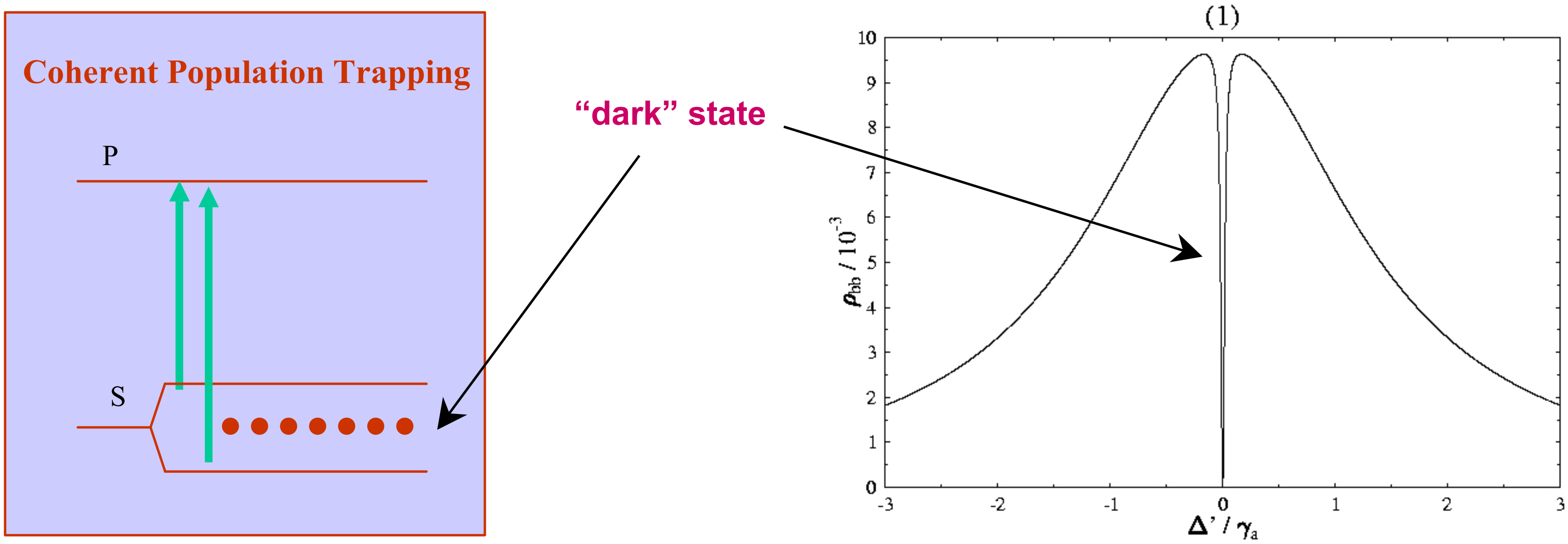








4.4 Coherent Population Trapping (CPT)



Potential advantages of using CPT:

- No microwave cavity
- Reduced light-shift

Open issues: 2-colours coherent laser source, signal contrast

4.5 Cold atoms clocks

Radiative forces: $\overrightarrow{E}(\vec{r},t) = \hat{e}\cdot E_0 \cdot \cos[\omega_L t + \phi(\vec{r})]$

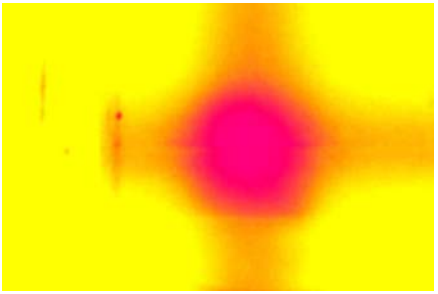
$$\overrightarrow{F} = \underbrace{\hat{e}\cdot d_{ab}\cdot u_{st}\cdot \nabla E_0(\vec{r})}_{\substack{reactive\ or\\ dipolar\ force}} + \underbrace{\hat{e}\cdot d_{ab}\cdot v_{st}\cdot E_0(\vec{r})\cdot \nabla\phi(\vec{r})}_{\substack{dissipative\ or\ radiation\\ pressure\ force}}$$

~ light-shift

~ absorption

Optical trapping (lattice, tweezers, etc.)

Optical molasses



Motivations: reduce the Doppler effect, increase interaction time, etc.

Sisyphus cooling: a combination of effects

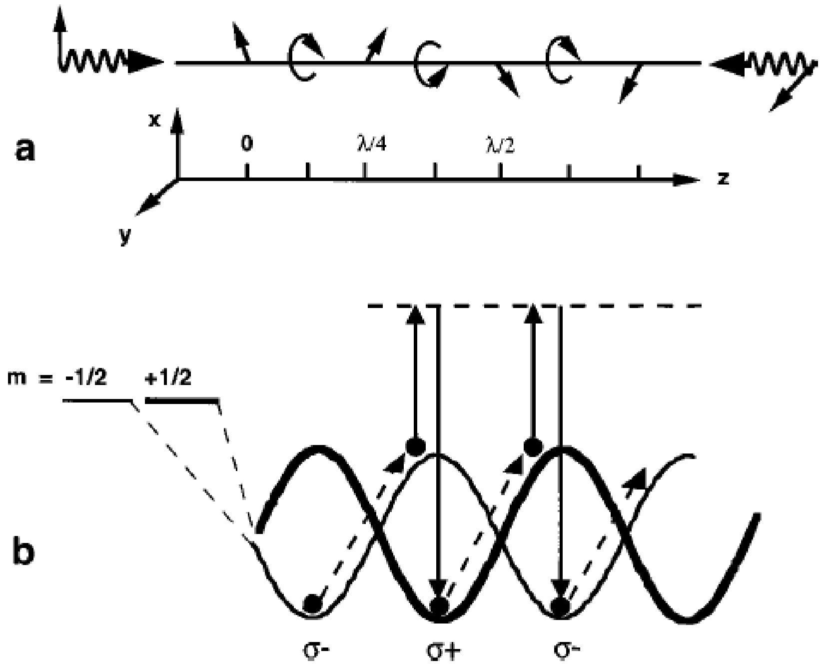
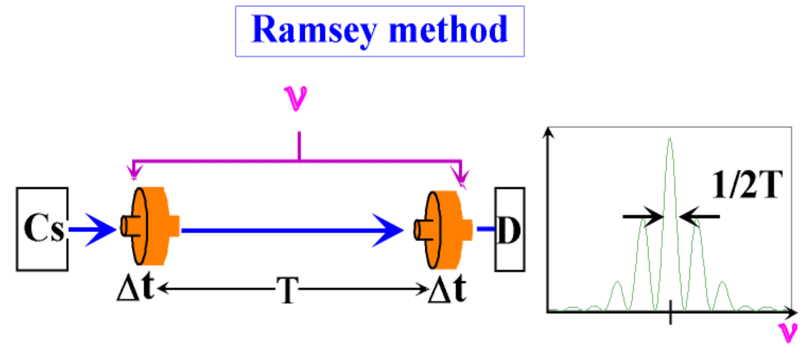
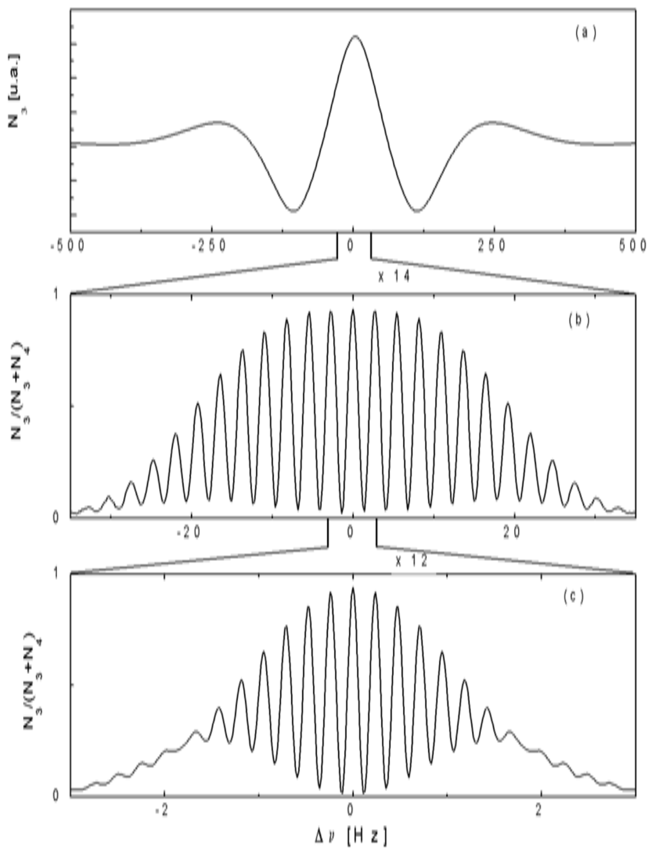


FIG. 18. (a) Interfering, counterpropagating beams having orthogonal, linear polarizations create a polarization gradient. (b) The different Zeeman sublevels are shifted differently in light fields with different polarizations; optical pumping tends to put atomic population on the lowest energy level, but nonadiabatic motion results in "Sisyphus" cooling.

Application to cold atoms clocks:





- Thermal beam:

v = 100 m/s, T = 5 ms

Δν = 100 Hz

- Fountain:

v = 4 m/s, T = 0.5 s

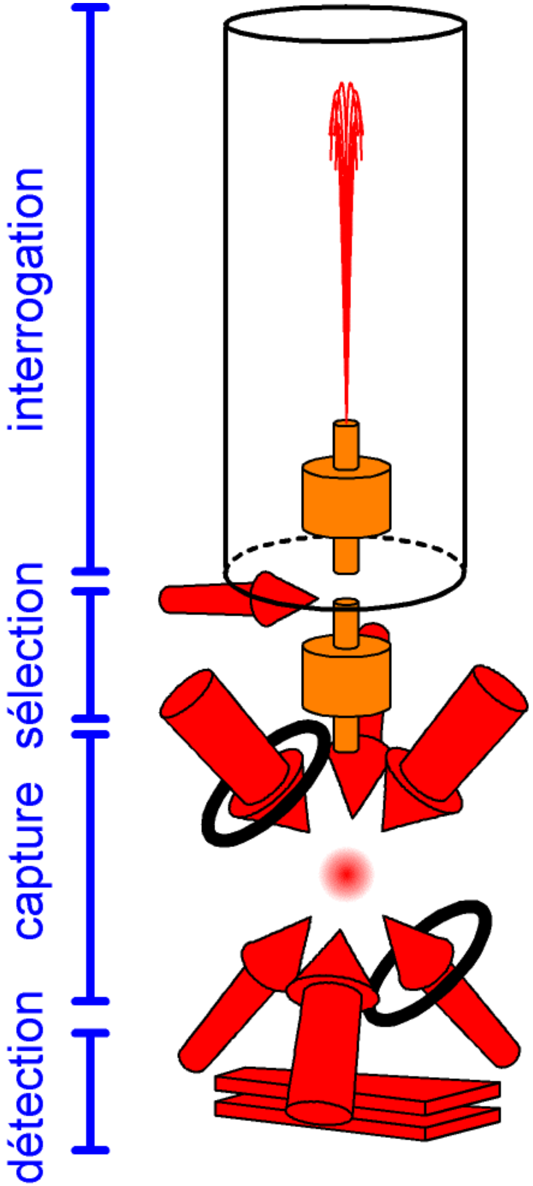
Δν = 1 Hz

- Cold beam in micro-gravity:

v = 0.05 m/s, T = 5 s

Δν = 0.1 Hz

Pulsed fountain



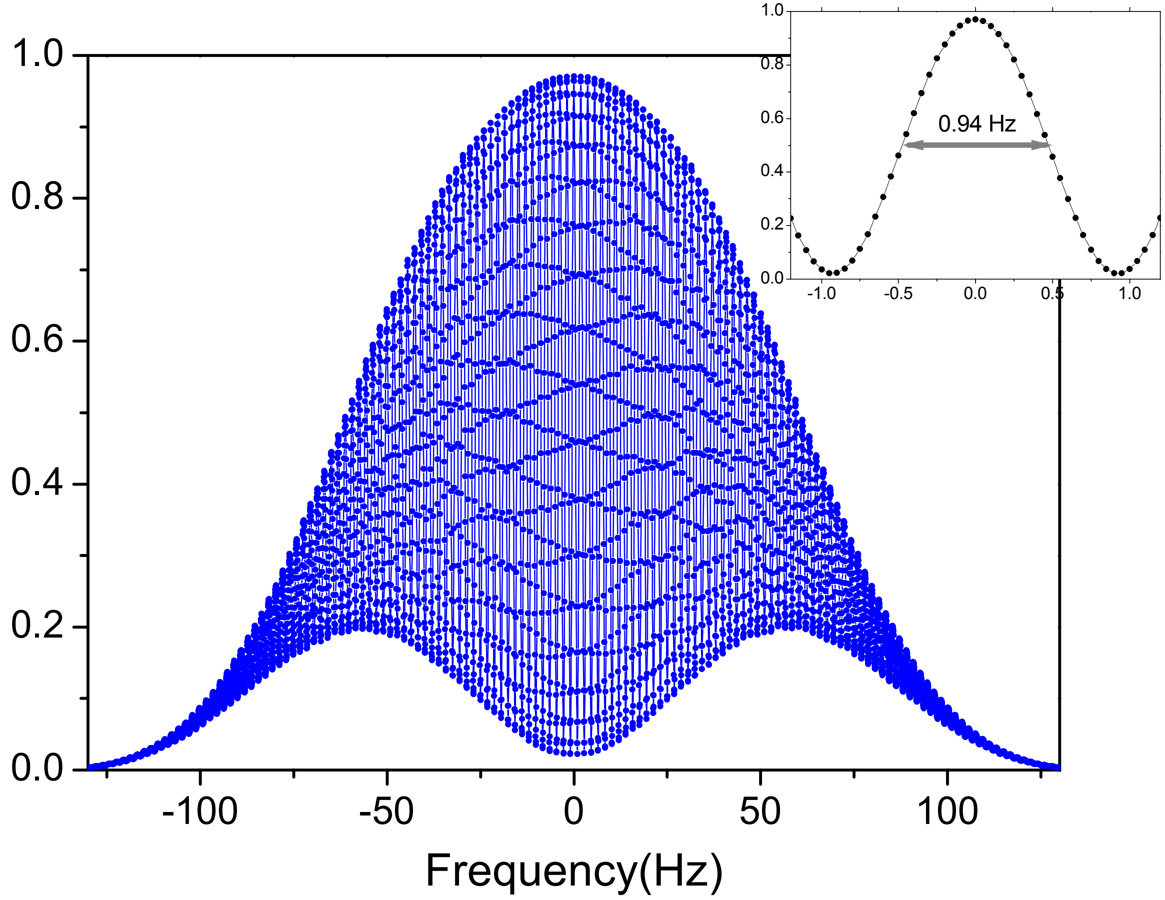


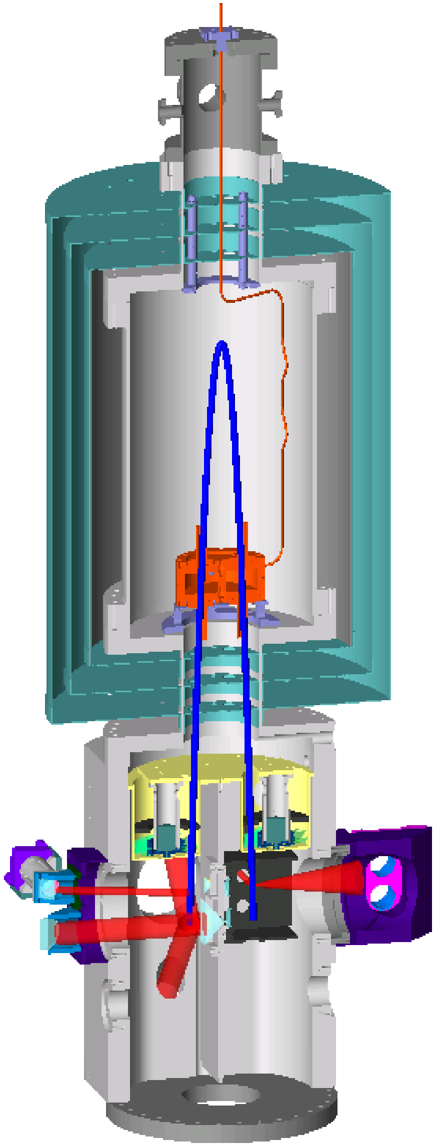
Table 5. Uncertainty contributions ($\times 10^{15}$) of the three caesium fountain frequency standards cited in the text. '<0.1' indicates that the component is smaller than 10^{-16} or is not considered to be of relevance by the authors, Lemonde *et al* (2001) for FO1, and Weyers *et al* (2001) for CSF1. For NIST-F1 the most recent data are given, valid for a 25-day period in February 2002 (Parker 2002).

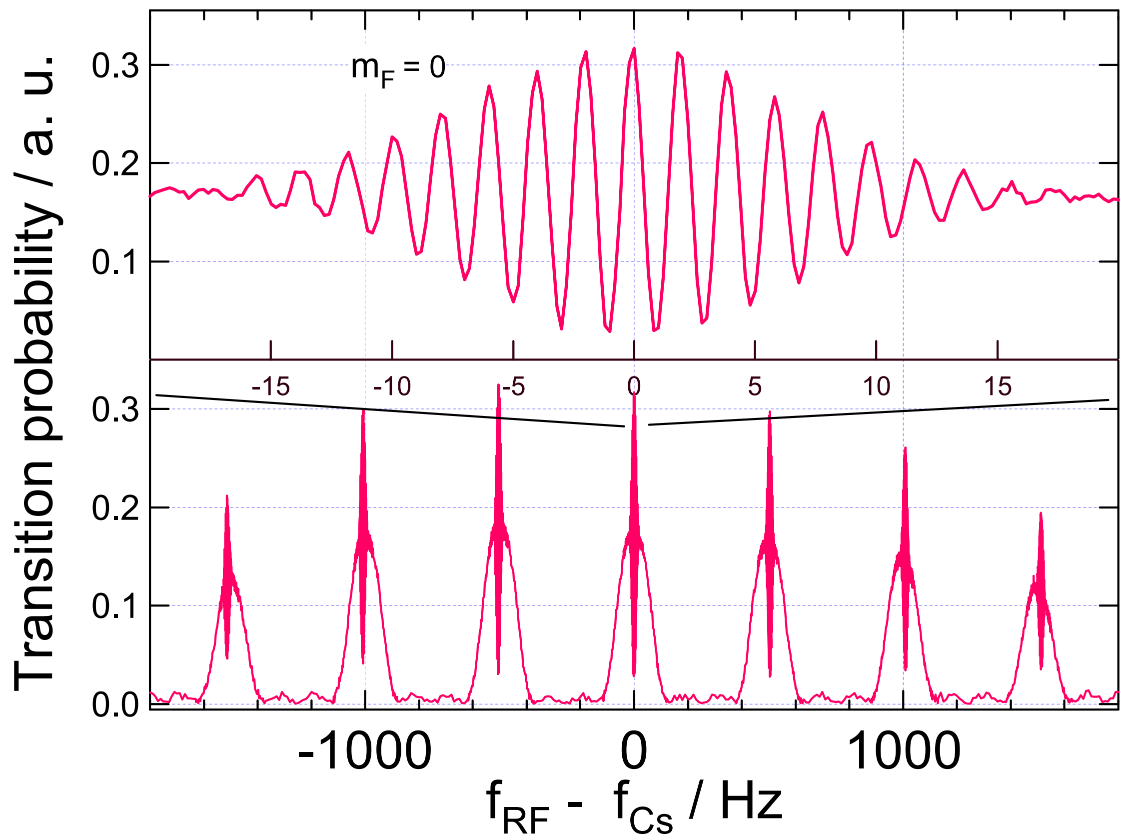
Cause of frequency shift	LPTF FO1	NIST-F1	PTB-CSF1
Quadratic Zeeman effect	<0.1	<0.1	<0.1
Quadratic Doppler effect	<0.1	<0.1	<0.1
AC Stark effect caused by thermal radiation	0.5	0.3	0.2
Cavity phase difference (distributed)	0.5	<0.1	0.5
Detuning of the microwave cavity	0.1	<0.1	<0.1
AC Stark effect caused by fluorescence radiation	<0.1	0.2	0.2
Asymmetric population of the Zeeman sublevels	0.4	<0.1	<0.1
Cold atom collisions	0.5	0.48	0.7
Electronics	0.3	0.2	0.2

Andreas Bauch

Meas. Sci. Technol. **14** (2003) 1159–1173

Continuous fountain





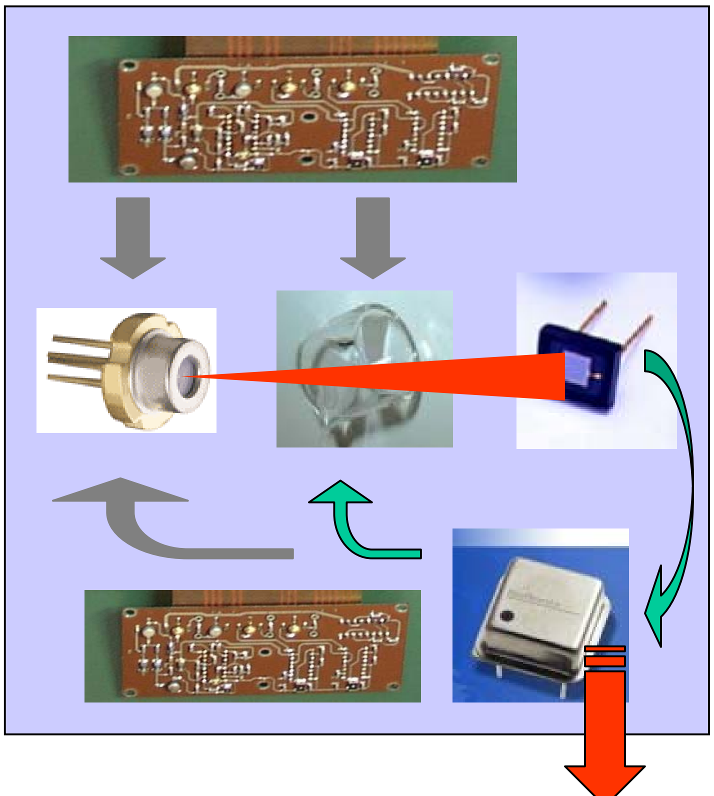
Main motivations:

reduce the effects of LO phase noise (stability) and collisions (accuracy)

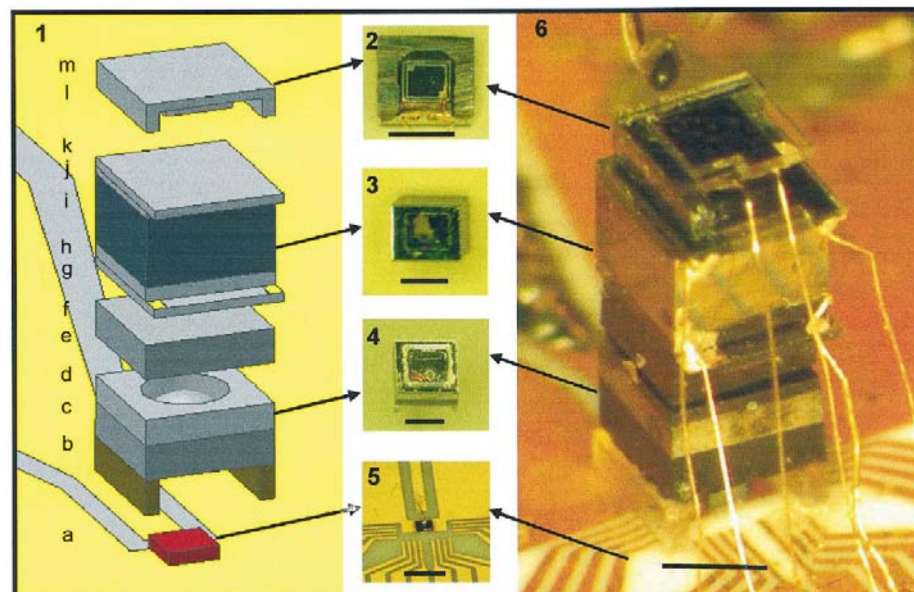
5. Trends for the (near) future

(Optical frequency standards: see next talk)

- Chip-scale atomic clocks



Stable reference



See Knappe et al., Appl. Phys. Lett., 85, (9), 2004

Collaboration

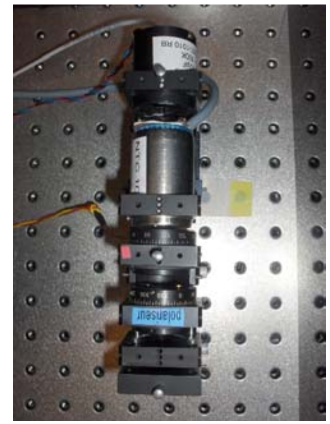
Université de Neuchâtel unine

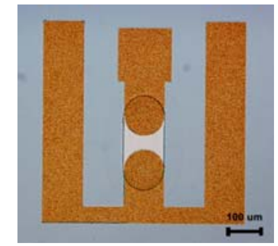
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

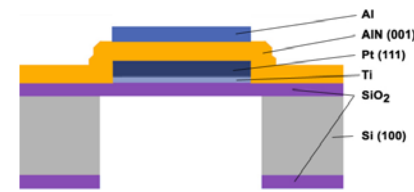
Mihq Microsystèmes et horloges quantiques

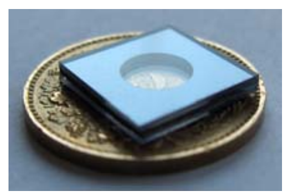
Conférence Universitaire Suisse

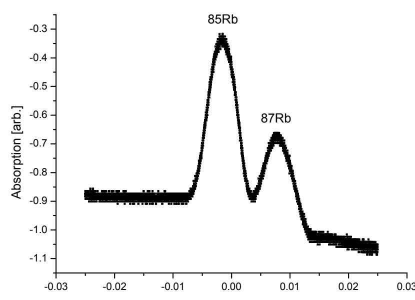
imt institut de microtechnique



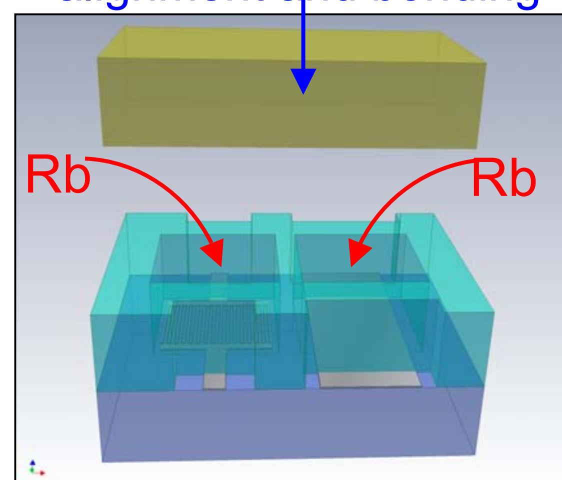






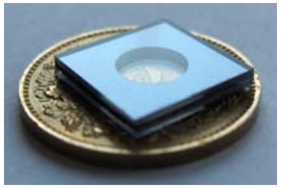


alignment and bonding



Physics & micro-technology in chip scale atomic clocks:

- Micro-fabrication of the atomic resonator
- Behavior of the confined atoms: collisions, wall-coating, etc.
- Ideal clock scheme: double resonance, Coherent Population Trapping, etc.



- Miniature optical source: control of the optical spectrum and its effects
- Miniature microwave sources: PM noise
- Overall clock electronics: consumption, etc.
- Assembly and packaging, reliability, wafer-scale production, etc.