Atomic Clocks and Frequency Standards

The Battel for Exactness

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July 07, 2010

Importance of (correct) Time Measurement

http://ageofsail.wordpress.com/

Importance of Time Measurement - Today

http://wikipedia.org/

Clocks & Frequency Standards

- fundamental importance time measurement
- challenge - man made clocks

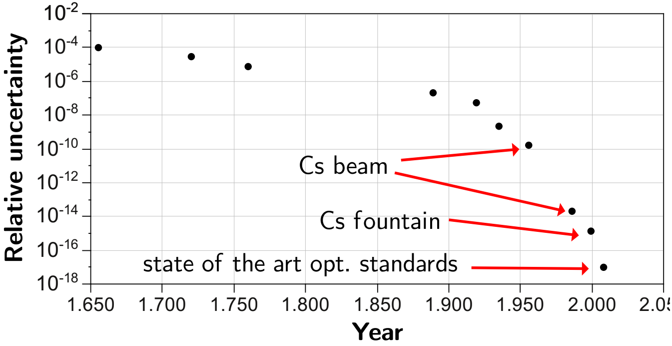
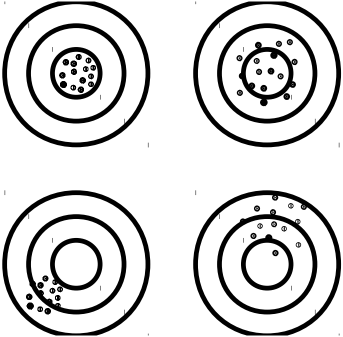


Figure: development clocks, partially after [1]

[1] F. Riehle, *Frequency Standards*, Wiley, 1st ed. 2004

- clock: basis frequency standard with frequency ν_0 measure amount of oscillation cycles, time T

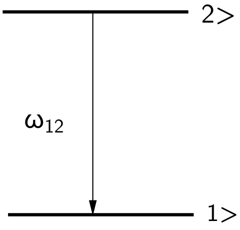
$$T = n \cdot \frac{1}{\nu_0}$$



- precise/stable, accurate frequency (short-, longterm stability)
- reproducibility
- frequencies in absolute unit in comparison to other standards
  - $\rightarrow$ intrinsic - primary standards
  - $\rightarrow$ calibration - back tracking

Clocks & Frequency Standards

- atomic clocks transition in microscopic quantum systems
- new SI definition of time unit in 1967: caesium primary standard



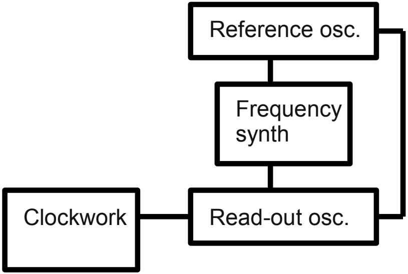
Definition

"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 the caesium 133 atom." [2]

[2] *Comptes Rendus de la 13e CGPM* (1967/68), 1969, 103

Atomic Clock Concept

- 2 separated oscillators
- one isolated reference, other read-out link

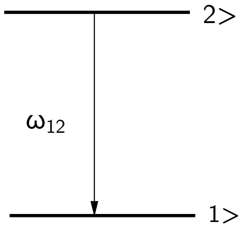


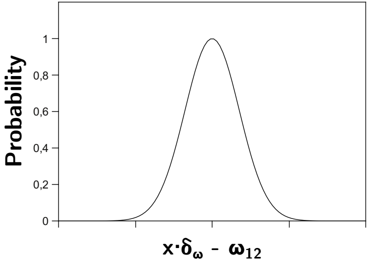
- reference oscillator quantum system
- read-out oscillator quartz crystal (piezoelectric)

Atomic Clock Concept

quantum system, two level system states $|1\rangle$, $|2\rangle$

1. preparation one of the states
2. interaction with electromagnetic field
3. measure probability for transition
4. lock read-out oscillator on frequency of probability maximum



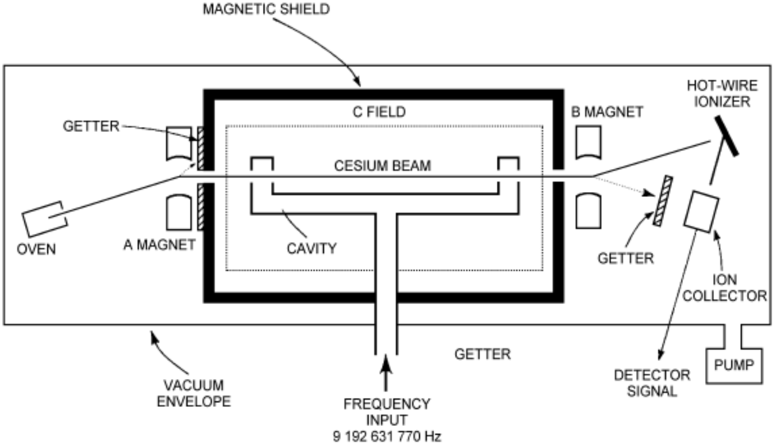


^{133}Cs Clocks - Beam clocks

http://www.nist.gov/

^{133}Cs Clocks - Beam clocks

- especial frequency standard
- basic setup NIST (from [5] D. Sullivan, J. Res. Natl. Inst. Stand. Technol.**106**, 2001)



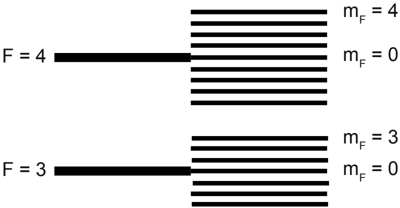
^{133}Cs Clocks - Beam clocks

- ^{133}Cs:

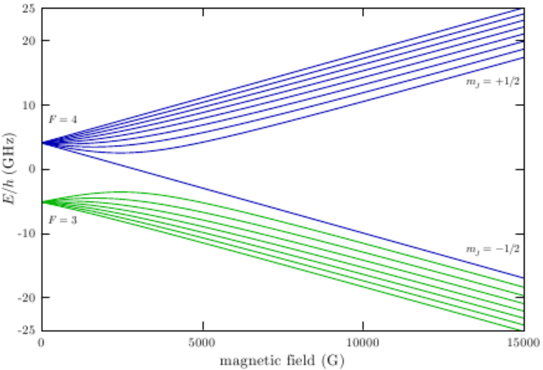
  nuclear spin $I = 7/2$
  total spin $J = 1/2$
  $\Rightarrow$ hyperfine structure, states $F = I \pm J = 3, 4$

- transition $|F = 4, m_F = 0\rangle \rightarrow |F = 3, m_F = 0\rangle$: $\Delta\nu = 919263770$ Hz (@ zero magnetic field)

- Zeeman split



^{133}Cs Clocks - Beam clocks



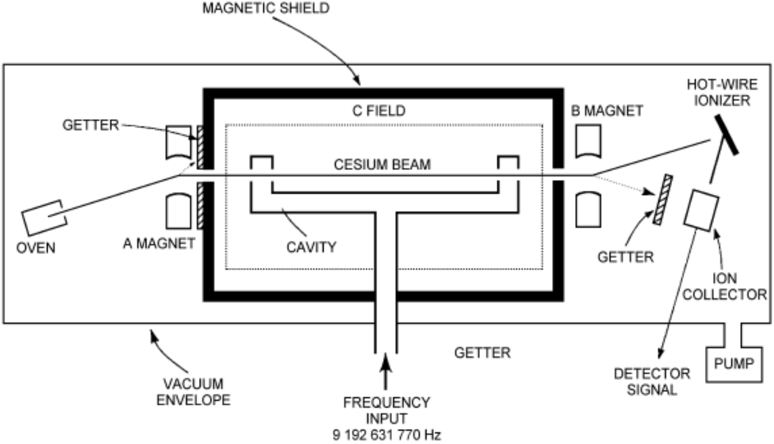
Zeeman split in external magnetic field

inhomogeneous field:

$$\vec{F} = -\mu_{\text{eff}} \nabla \vec{B}$$

[6] Daniel A. Steck, *"Cesium D Line Data,"* (revision 2.1.2, 12 August 2009)

^{133}Cs Clocks - Beam clocks



Challenges - Broadening Processes

Aim

Interest in high $Q = \frac{\omega_0}{\Delta\omega}$

Broadening processes:

- natural lifetime τ_l: $\Delta\omega_l \propto \frac{1}{\tau_l}$

  $\Rightarrow$ negligible i.e. ^{133}Cs stable

- Doppler broadening

  from energy, momentum conservation

  $+$ absorption, $-$ emission, relativistic calculation

$$\Rightarrow \; \hbar\omega = \hbar\omega_{12} + \hbar\vec{v}_{1,2} \cdot \vec{k} \pm \frac{(\hbar\omega)^2}{2m_0c^2} - \hbar\omega_{12}\frac{v_{1,2}^2}{2c^2} + \ldots$$

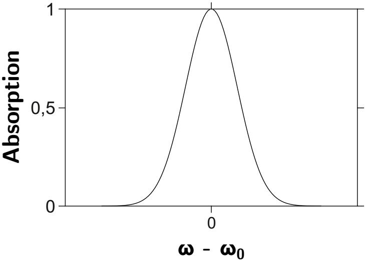
Challenges - Broadening Processes

$$\hbar\omega = \hbar\omega_{12} + \hbar\vec{v}_{1,2}\cdot\vec{k} \pm \frac{(\hbar\omega)^2}{2m_0c^2} - \hbar\omega_{12}\frac{v_{1,2}^2}{2c^2} + \ldots$$

2nd term first-order Doppler effect $\Rightarrow$ Gaussian broadening

$$FWHM = \omega_{12}\sqrt{2\ln 2\frac{k_BT}{mc^2}}$$

3nd term recoil effect
4nd term second-order Doppler effect



$\Rightarrow$ avoided by low temperature regime

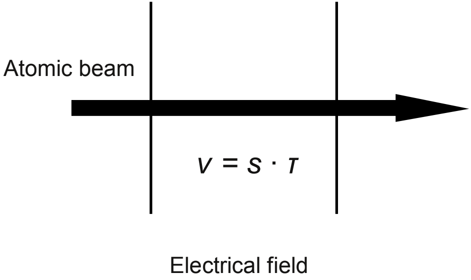
Challenges - Broadening Processes

- Collision broadening: $\Delta\omega_{\text{col}} \propto \dfrac{1}{\tau_{\text{col}}} \propto p \Rightarrow$ pressure reduction
- Intersection Time broadening

  important contribution to the linewidth broadening

$$\Delta\omega_{\text{it}} \propto \frac{1}{\tau_{\text{it}}}$$

solution enhancement τ_{it}



Challenges - Broadening Processes

- How slow an atomic beam can be made?
- Homogeneity of the electromagnetic field?

$\Rightarrow$ concept Ramsey spectroscopy (Nobel prize 1989)

Rabi Flopping

- atomic beam *one* interaction
- two level system

$\Rightarrow$ solution: oscillating occupation probability

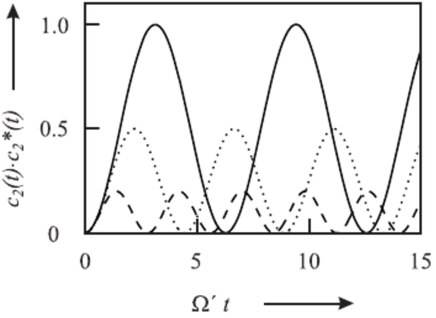


Figure: from [1] F. Riehle, *Frequency Standards*

- excited state $|2\rangle$:

$$p_2(t) = \frac{\Omega_R}{\Omega'_R} \sin^2 \frac{\Omega'_R t}{2}$$
$$\Omega'^2_R = \Omega^2_R + \Delta\omega^2$$

Ω_R: Rabi frequency

- amplitude decrease with $\Delta\omega$

Ramsey Spectroscopy

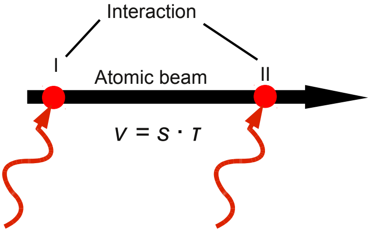
- idea two separated interactions time τ and between no field in between for time T

  $\Rightarrow$ probability for transition interference pattern

- near resonance $|1\rangle \rightarrow |2\rangle$

$$p(\tau + T + \tau) \simeq \frac{1}{2}\sin^2 \Omega_R \tau \left(1 + \cos 2\pi(\nu - \nu_{12})T\right)$$

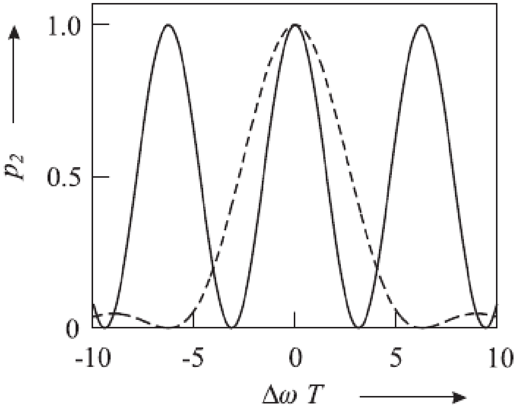
$$\Rightarrow \; FWHM = \frac{1}{2T}$$



maximum for $\Omega_R \tau = \frac{\pi}{2} \rightarrow \pi/2$ pulses

[3] M. Ramsey, Phys. Rev. **78** (6), 1950
[1] F. Riehle, *Frequency Standards*

Ramsey Spectroscopy



- enhancement signal linewidth
- amplitude, period nearly unaffected

[1] F. Riehle, *Frequency Standards*

Ramsey Spectroscopy - pseudo spin picture

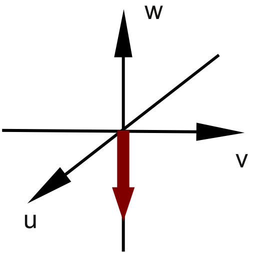
density matrix ρ_{11} ρ_{22} probability state $|1\rangle$ $|2\rangle$:

$$\rho = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix}$$

Optical Bloch equations (with $\tilde{\rho}_{12} \equiv e^{-i\delta t}\rho_{12}$,$\tilde{\rho}_{21} \equiv e^{+i\delta t}\rho_{21}$):

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} \tilde{\rho}_{21} + \tilde{\rho}_{12} \\ i(\tilde{\rho}_{21} - \tilde{\rho}_{12}) \\ \rho_{22} - \rho_{11} \end{pmatrix}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} \Omega_R \\ 0 \\ \delta \end{pmatrix} \times \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$



*) i.e. P. Meystre and M. Sargent, *Elements of Quantum Optics*

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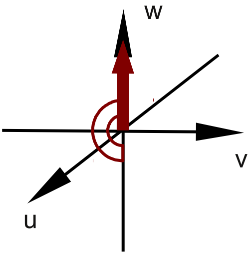

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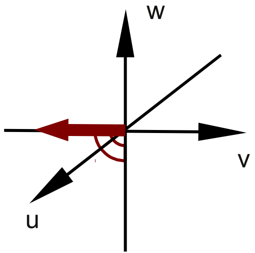

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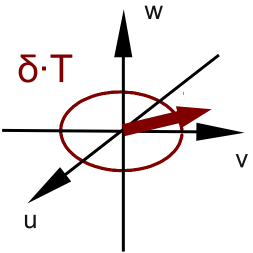

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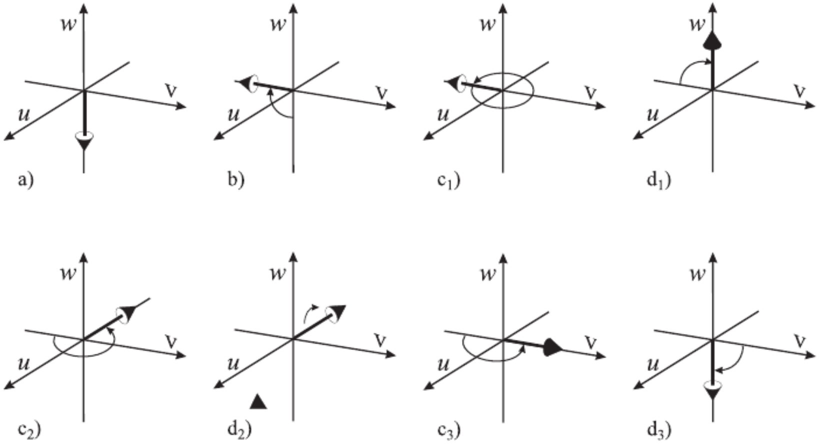
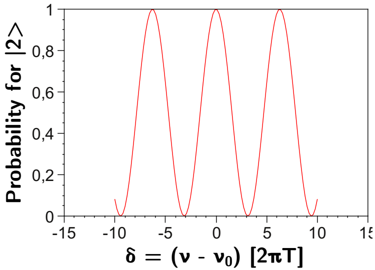
Ramsey Spectroscopy - pseudo spin picture



from [1] F. Riehle, *Frequency Standards*

Ramsey Spectroscopy - pseudo spin picture

interference pattern



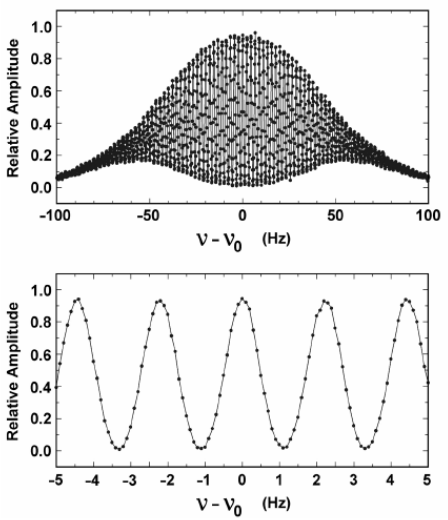
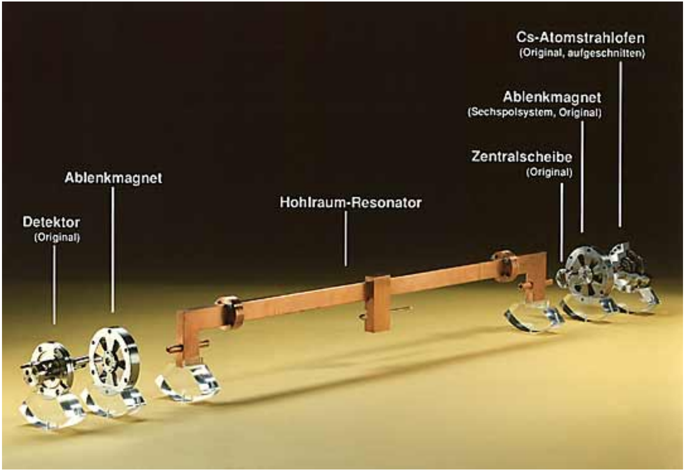


Figure: from [5] D. Sullivan, J. Res. Natl. Inst. Stand. Technol.**106**, 2001

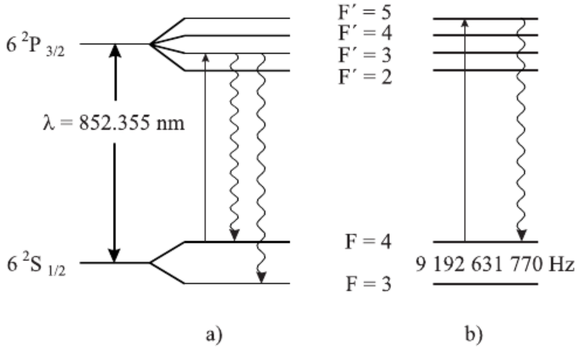
^{133}Cs Clocks - Beam clocks



http://www.ptb.de/

^{133}Cs Clocks - Beam clocks, optical pumping

- enhance signal to noise ratio
- optical pumping for state selection
- detection optical transition

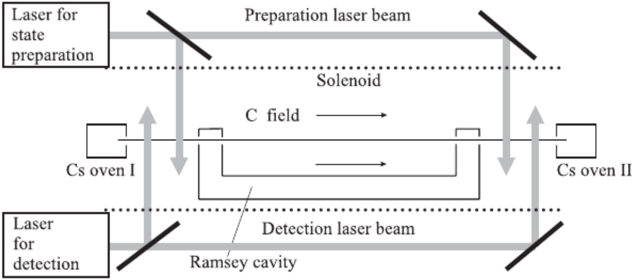


- a) pumping, b) detection flourescence photons

from [1] F. Riehle, *Frequency Standards*

^{133}Cs Clocks - Beam clocks, optical pumping

- basic layout



from [1] F. Riehle, *Frequency Standards*

^{133}Cs Clocks - Beam clocks, performance

- challenge cavity:

  length ($\Delta\nu = 1/2T$)

  versus

  additional phase shift due to manufacturing limits

  relative uncertainty:
- NIST: NIST-7: 4.4×10^{-15}
- PTB: CS1: 8×10^{-15}

[5] D. Sullivan, *et al*, J. Res. Natl. Inst. Stand. Technol.**106**, 2001

[7] A. Bauch, **42** (2005),Metrologia **42**, 2001

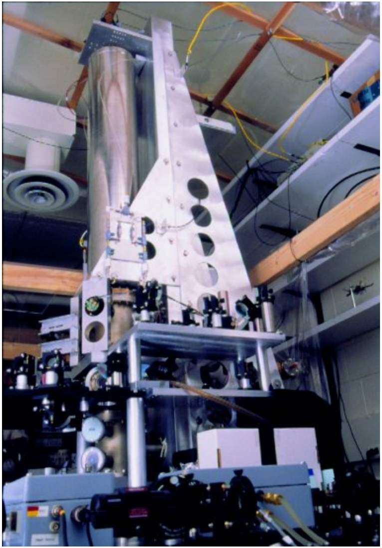
^{133}Cs Clocks - fountain clocks

One step further!

- laser cooled atomic clocks
- two approaches:

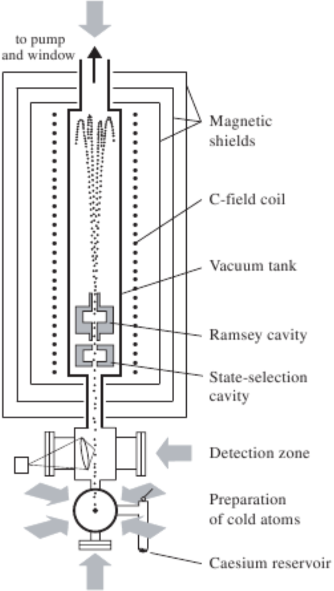
  $\rightarrow$ enhance T
  $\rightarrow$ reduce phase shift from cavity

- fountain design



http://www.nist.gov/

^{133}Cs Clocks - fountain clocks



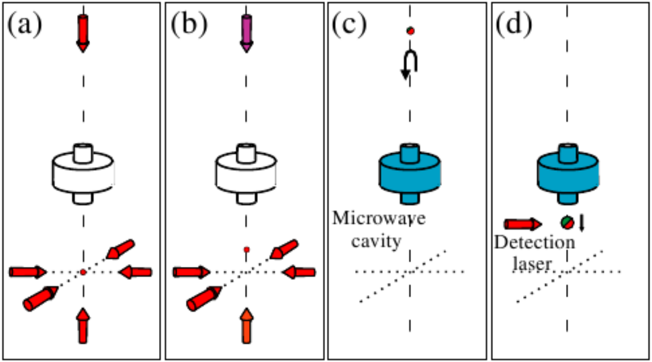
- two interactions $\pi/2$-pulses (Ramsey)
- one cavity

  $\Rightarrow$ reduced phase shift
- laser cooled atoms 2 μK, enhanced T

[8] R. Wynands *et al*, Metrologia **42**, 2005

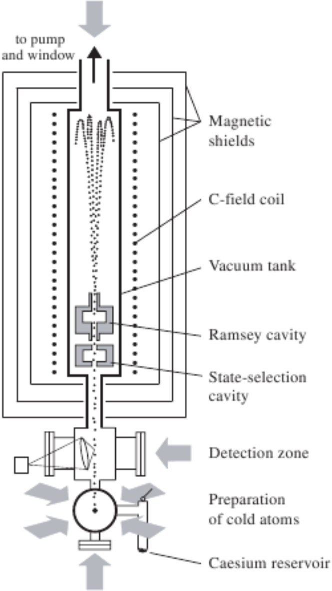
^{133}Cs Clocks - fountain clocks

process



[8] R. Wynands *et al*, Metrologia **42**, 2005

^{133}Cs Clocks - fountain clocks



- cold atoms - Magneto Optical Trap or Optical Molasse
- lifting atoms with $c\delta_\nu/\nu_{12}$ for

  laser upwards: $\nu = \nu_{12} + \delta_\nu$

  laser downwards: $\nu = \nu_{12} - \delta_\nu$
- state selection:

  from cooling in $|F = 4, m_F\rangle$

  π-pulse $|F = 4, m_F = 0\rangle \rightarrow |F = 3, m_F = 0\rangle$

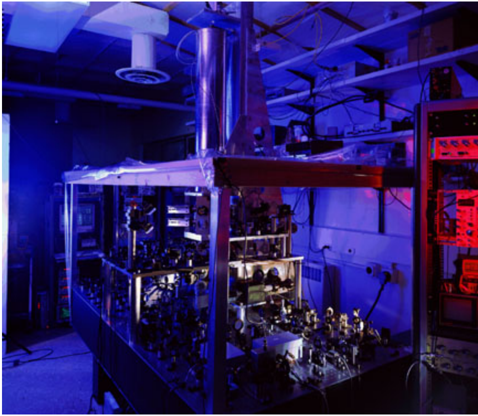
  "laser-pushing" other states $|F = 4, m_F\rangle \rightarrow |F' = 5, m_F\rangle$

[8] R. Wynands *et al*, Metrologia **42**, 2005

^{133}Cs Clocks - fountain clocks, performance

- today's measurement standard PTB: CSF2 2009
- relative uncertainties:

PTB CSF2: 0.8×10^{-15}
NIST NIST-F1: 1×10^{-15}
(0.5×10^{-15})

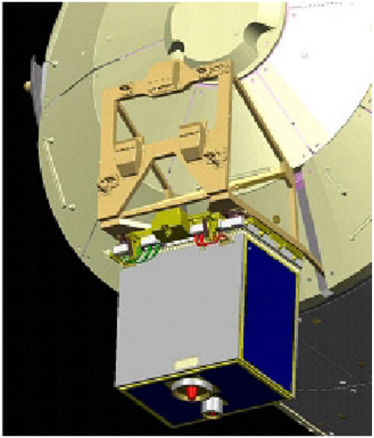


http://www.nist.gov/

^{133}Cs Clocks - fountain clocks, performance

remaining problems:

- cold collision shift
  - $\Rightarrow$ density reduction
  - $\rightarrow$ increased statistical noise
  - $\Rightarrow$ other atomic species ^{87}Rb
- increasing flight time
  - $\rightarrow$ not possible on earth
  - $\Rightarrow$ experiments in micro gravity



http://www.esa.int/

Outlook

http://www.dlr.de/

- 2001 PHARO project
- 2010 ISS module ACES
  uncertainty $\sim 10^{-16}$ regime

- next generation on earth optical frequency standards for atomic clocks
- uncertainty $< 10^{-17}$ regime

Bibliography

- [1] F. Riehle, *Frequency Standards*, Wiley, 1st ed. 2004
- [2] *Comptes Rendus de la 13^e CGPM* (1967/68), 1969, 103
- [3] M. Ramsey, *A Molecular Beam Method with Separated Oscillating Fields*, Phys. Rev. **78** (6), 1950
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- [6] Daniel A. Steck, *"Cesium D Line Data,"* available online at `http://steck.us/alkalidata` (revision 2.1.2, 12 August 2009)
- [7] A. Bauch, *The PTB primary clocks CS1 and CS2* Metrologia **42**, 2005, J. Res. Natl. Inst. Stand. Technol.**106**, 2001
- [8] R. Wynands *et al*, *Atomic fountain clocks* ,Metrologia **42**, 2005