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Quantum state preparation and laser cooling of a continuous atomic fountain with a single optical lattice

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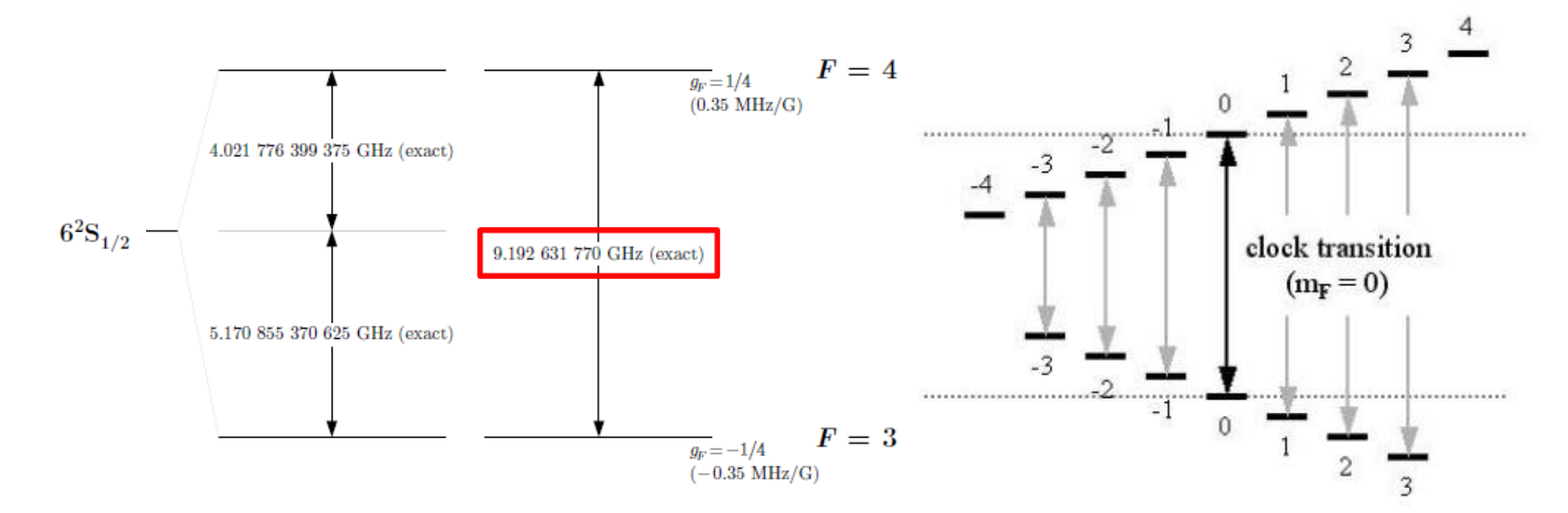
Introduction

We use two lasers optical pumping on a caesium atomic fountain in order to prepare all atoms in the same quantum ground state. A first laser excites the F=4 ground state to pump the atoms toward F=3 while a second π-polarized beam excites the F=3→F'=3 transition to produce Zeeman pumping toward m=0. To avoid trap states, we implemented the first laser in a 2D optical lattice geometry thereby creating polarization gradients. This configuration has the advantage to produce Sisyphus cooling if the laser is tuned between the F=4→F'=4 and F=4→F'=5 transitions of the D2 line, which is important to balance the heating produced by optical pumping. We have measured a total atomic flux (in the detection zone) of $7\cdot10^6$ atoms/s, shot-noise limited. Theoretical calculations predict that 98% of these atoms can be pumped in the m=0 clock state and preliminary experiments show an 80% efficiency.

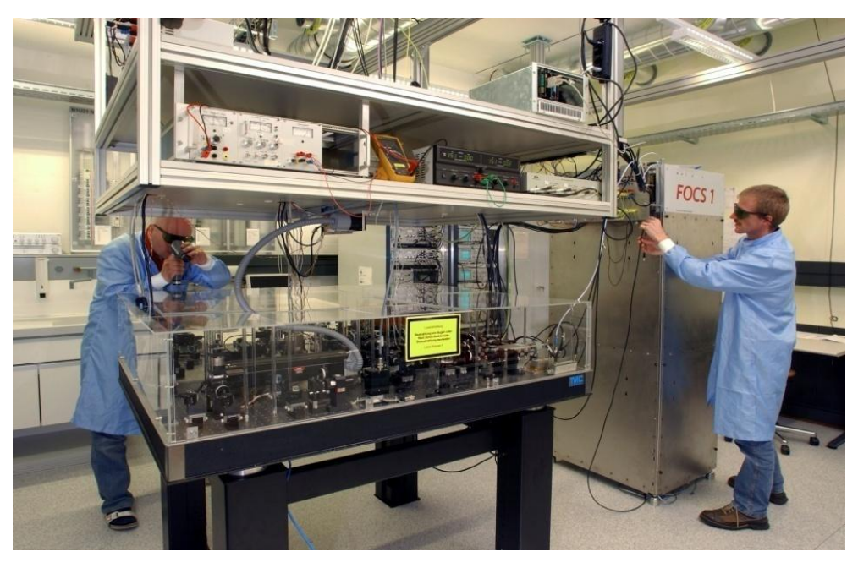
Definition and realization of the second

Definition of the second

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.



FOCS-1 and FOCS2 are two primary frequency standards developed by LTF in collaboration with METAS for the realization of the second.



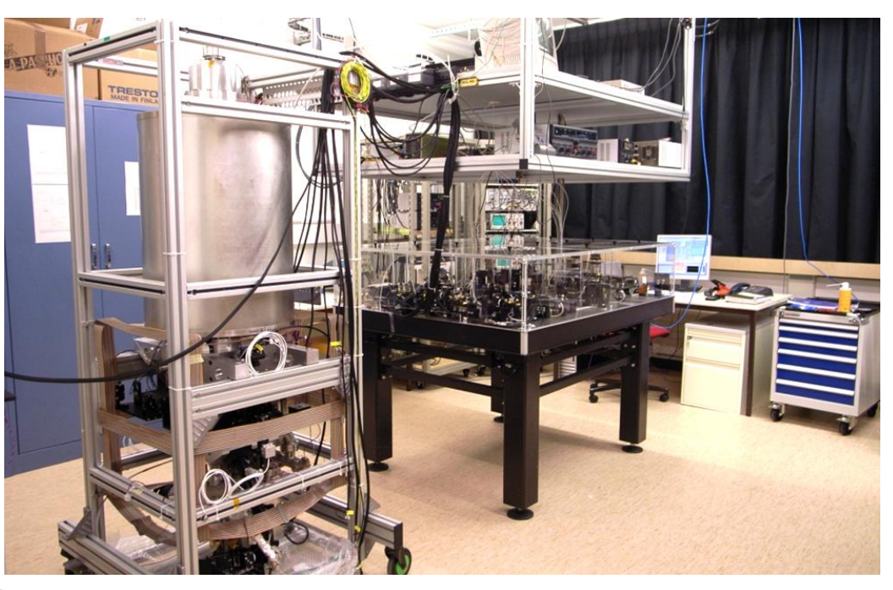
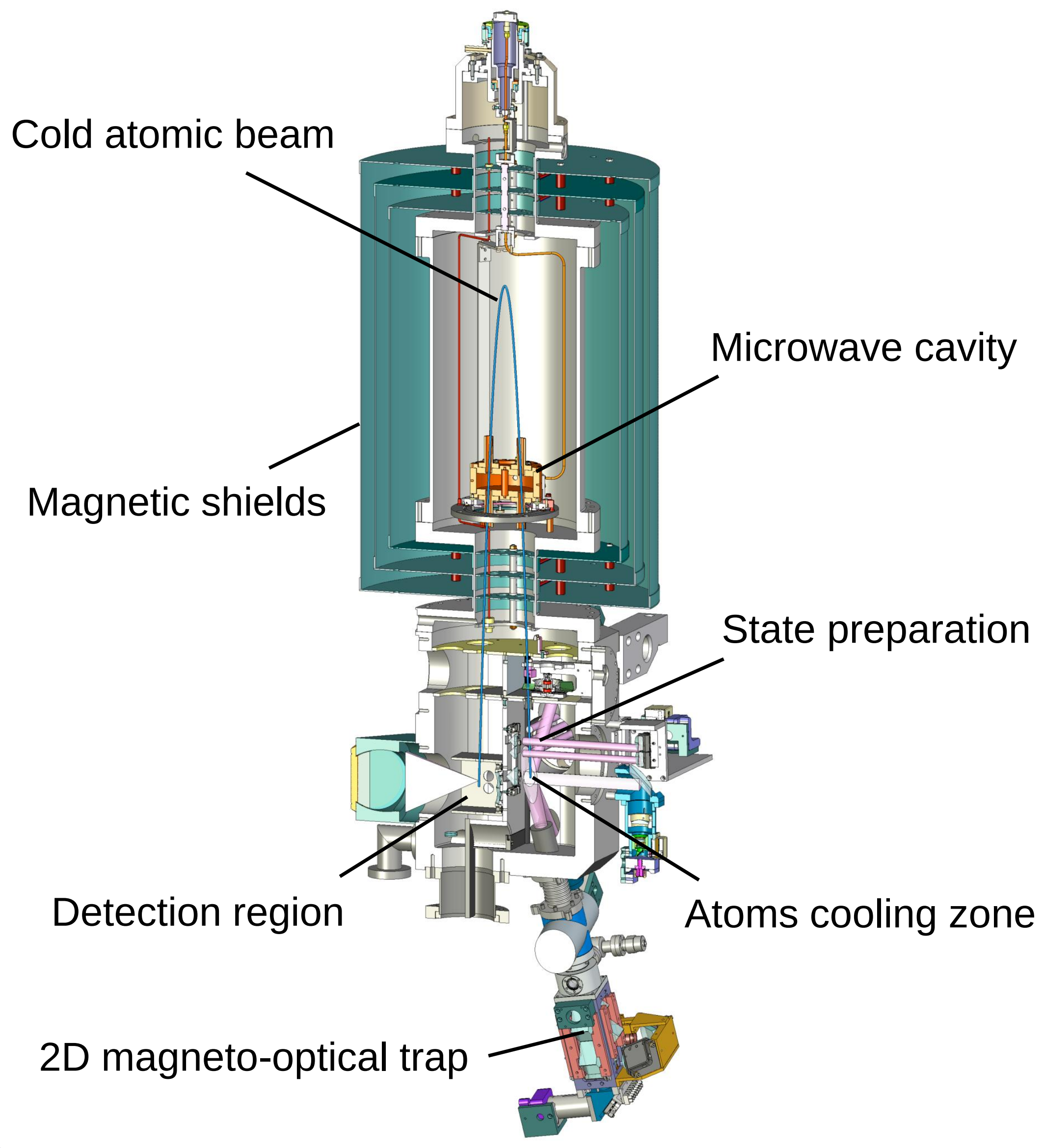


Fig.1 FOCS-1 is now in the Swiss National Institute of Metrology, METAS, Bern.

Fig.2 FOCS-2 under development at LTF, Neuchâtel.

Swiss primary frequency standard: Continuous atomic fountain clock



Motivation

Theoretical clock instability

$$\boxed{\sigma_y(\tau)=\frac{\tau^{-1/2}}{\pi\,Q(S/N)}}$$

Integration time

Frequency fluctuations

$$y=\frac{\delta\nu_0}{\nu_0}$$

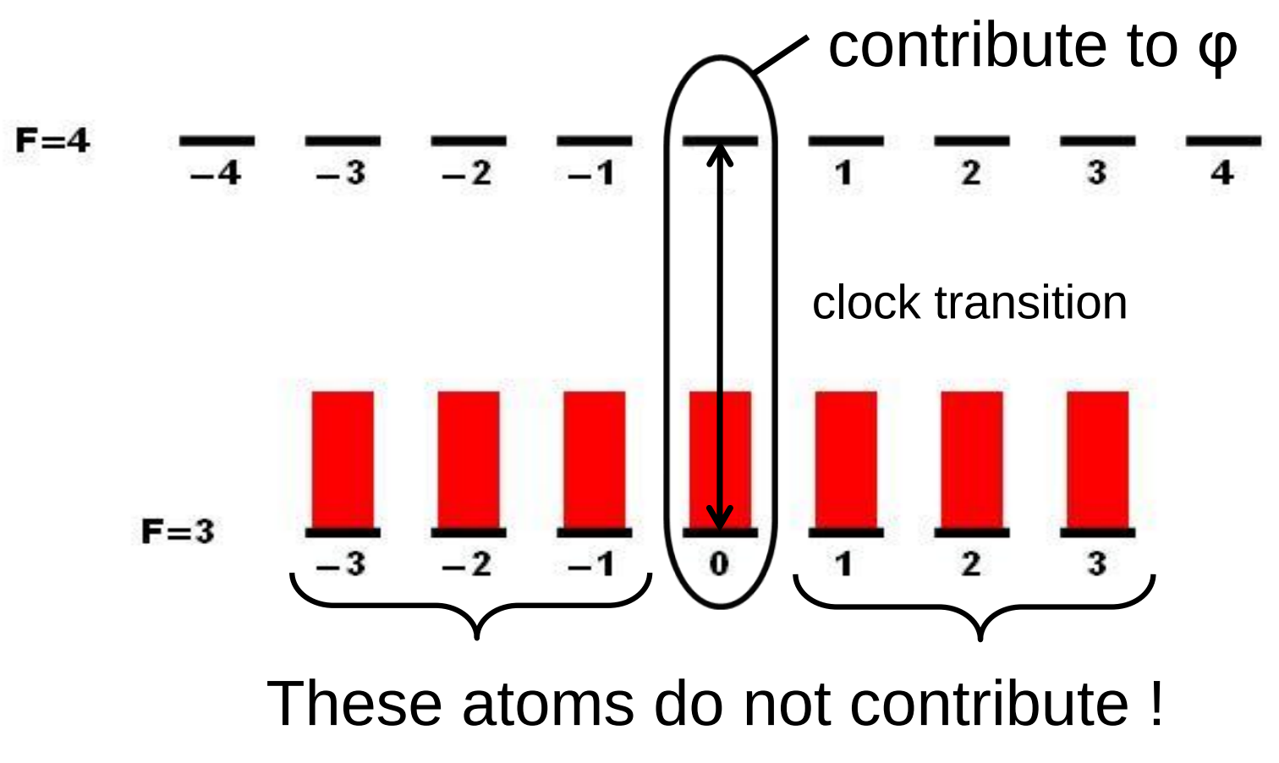
Resonance quality factor

$$Q=\frac{\nu_0}{\Delta\nu}\approx10^{10}$$

Shot noise limited signal-to-noise ratio

$$(S/N)=\sqrt{\frac{\varphi}{2}}$$

Only the atoms in state F=3, m=0 contribute to the atomic clock resonance :



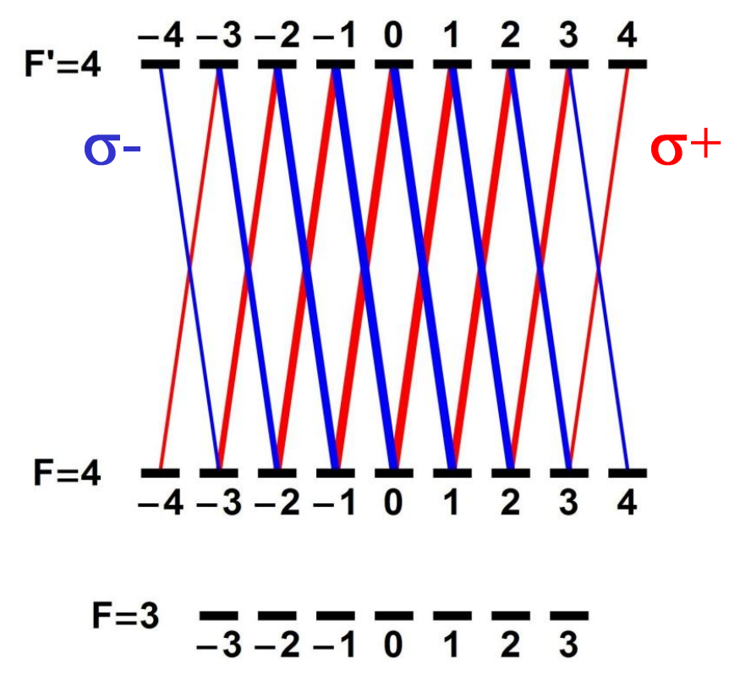
These atoms do not contribute !

To improve the stability, we want to put all the atoms in the F=3,m_f=0 clock transition by two lasers optical pumping

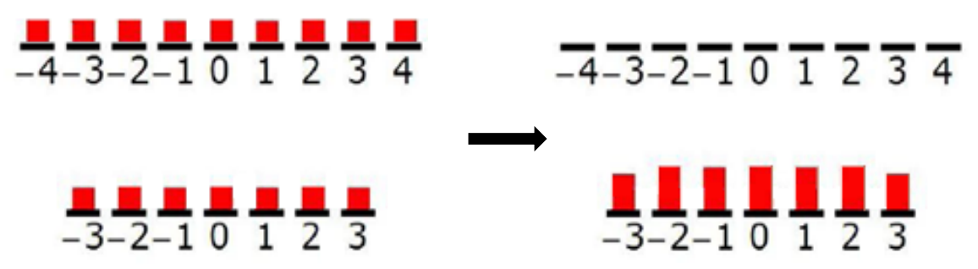
Quantum state preparation

One laser optical pumping

Idea: use laser excitation of atoms in F=4 to put them in F=3 after a few cycles.

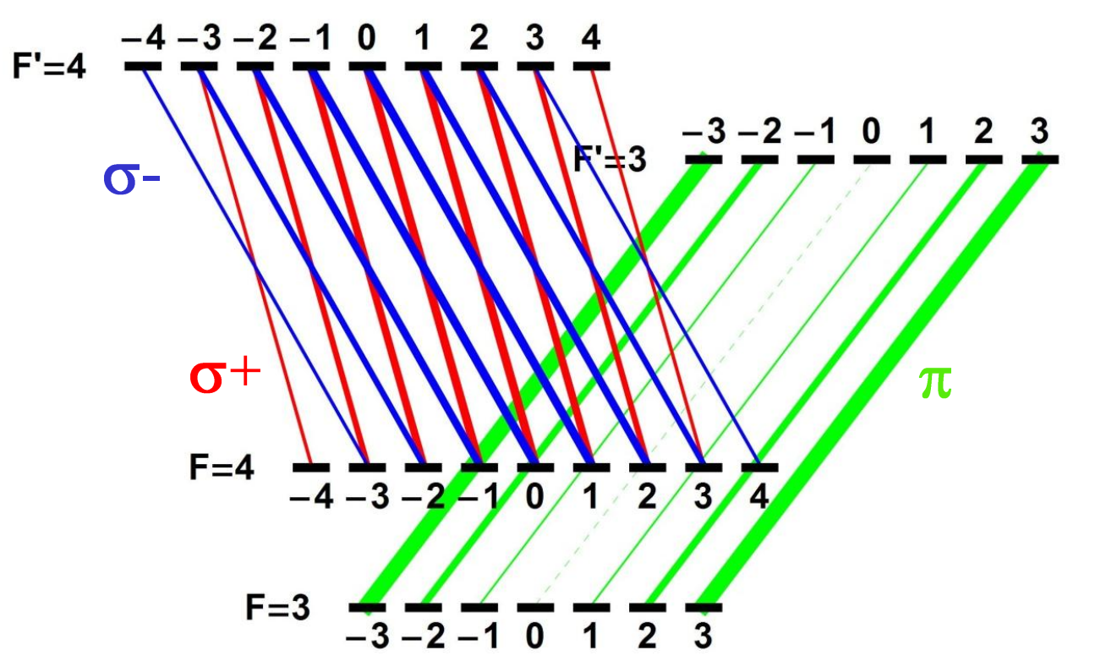


Result: all atoms in F=3, m=-3,…,+3

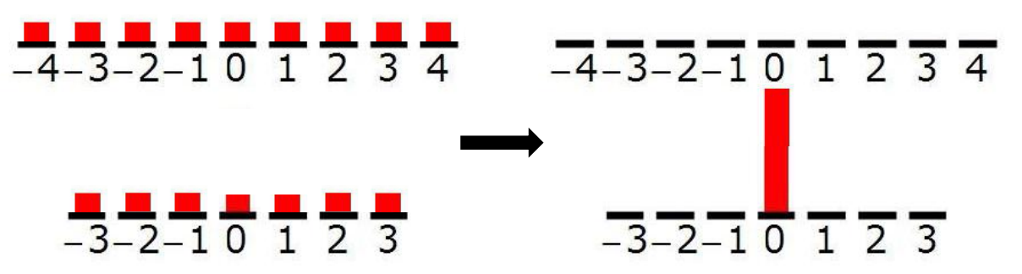


Two lasers optical pumping

- 1^{st} laser for hyperfine pumping to F=3
- 2^{nd} laser for Zeeman pumping to m=0



Result: all atoms in one state F=3, m=0

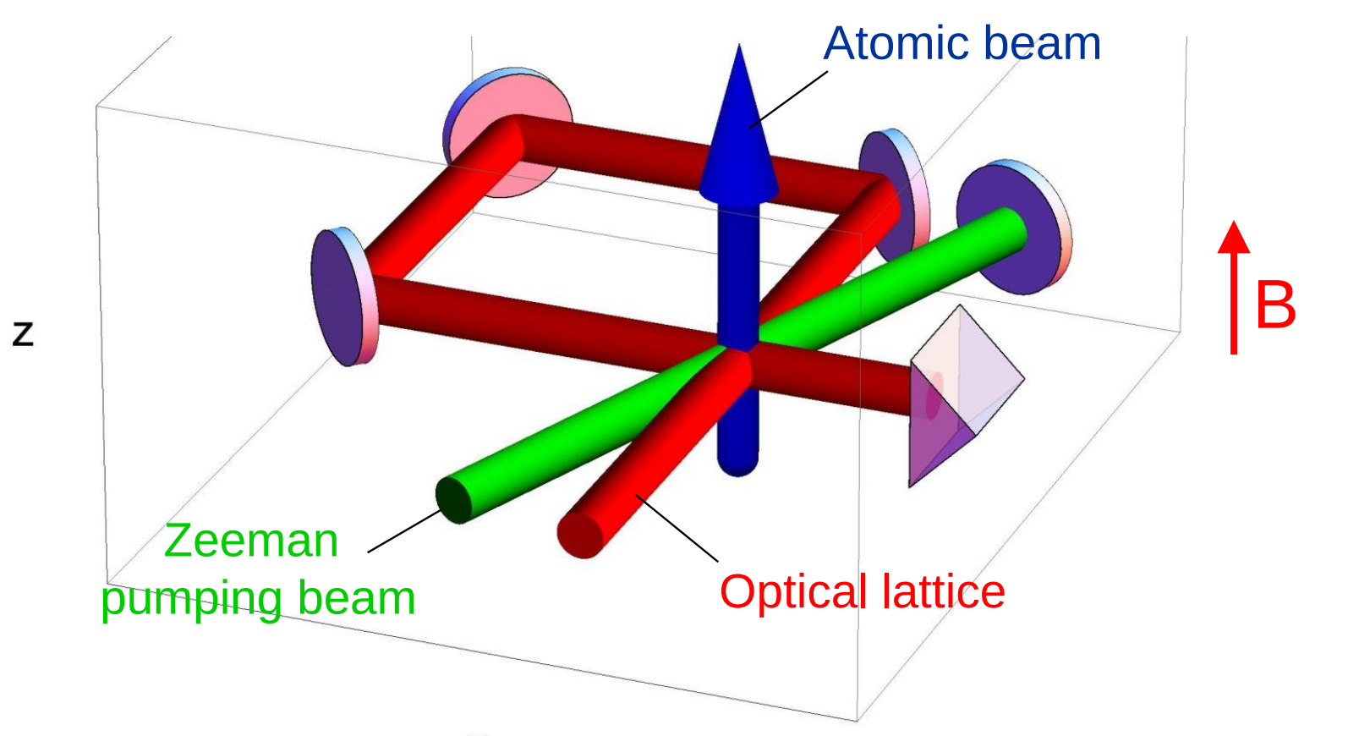


Practical difficulties

1. **Existence of coherent trap states**
   The efficiency of hyperfine pumping may be reduced by the existence of coherent trap states. Solutions: apply a magnetic field or scramble the laser polarization.
2. **Long Zeeman pumping time (15μs)**
   The number of pumping cycles to reach m=0 is ten times higher than for hyperfine pumping. Not a problem with cold atoms.
3. **Spontaneous emission produces heat**
   Spontaneous emission (>100 photons) significantly increases the temperature of the cold atomic beam. A possible solution would be to combine pumping and cooling.

Proposed solution

1. Zeeman pumping with π **polarized laser**.
2. Hyperfine pumping with an **optical lattice** to create a strong polarization gradient.
3. Lattice laser midway between 4-4' and 4-5' to produce Sisyphus cooling.



Two-lasers pumping : numerical simulations

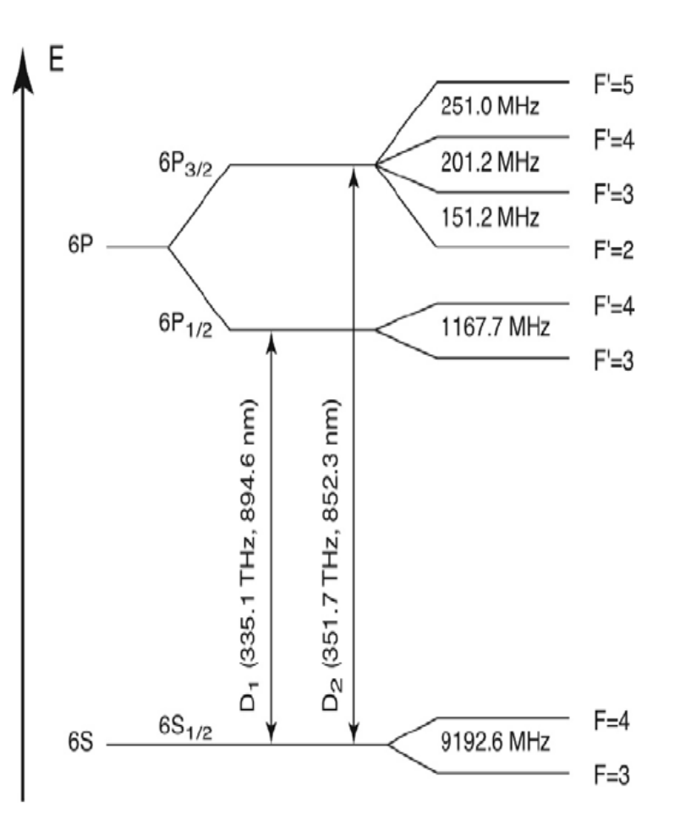
Theoretical model

$$\frac{dn_{e_{1i}}}{dt}=\sum_l W_{g_l\to e_{1i}}n_{g_l}-\sum_l W_{e_{1i}\to g_l}n_{e_{1i}}-\Gamma n_{e_{1i}}$$

$$\frac{dn_{e_{2j}}}{dt}=\sum_k W_{f_k\to e_{2j}}n_{f_k}-\sum_k W_{e_{2j}\to f_k}n_{e_{2j}}-\Gamma n_{e_{2j}}$$

$$\frac{dn_{f_k}}{dt}=-\sum_j W_{f_k\to e_{2j}}n_{f_k}+\sum_j W_{e_{2j}\to f_k}n_{e_{2j}}+\sum_j A_{e_{2j}\to f_k}n_{e_{2j}}+\sum_i A_{e_{1i}\to f_k}n_{e_{1i}}$$

$$\frac{dn_{g_l}}{dt}=-\sum_i W_{g_l\to e_{1i}}n_{g_1}+\sum_i W_{e_{1l}\to g_l}n_{e_{1i}}+\sum_i A_{e_{1i}\to g_l}n_{e_{1i}}+\sum_j A_{e_{2j}\to g_l}n_{e_{2j}}$$



Absorption and stimulated emission

$$W_{e_{1(2)}\to f(g)}=\frac{3}{4}\frac{\lambda_i^3}{\pi^2hc}\frac{I}{\Delta\nu_L}A_{e_{1(2)}\to f(g)}\varepsilon_q^2$$

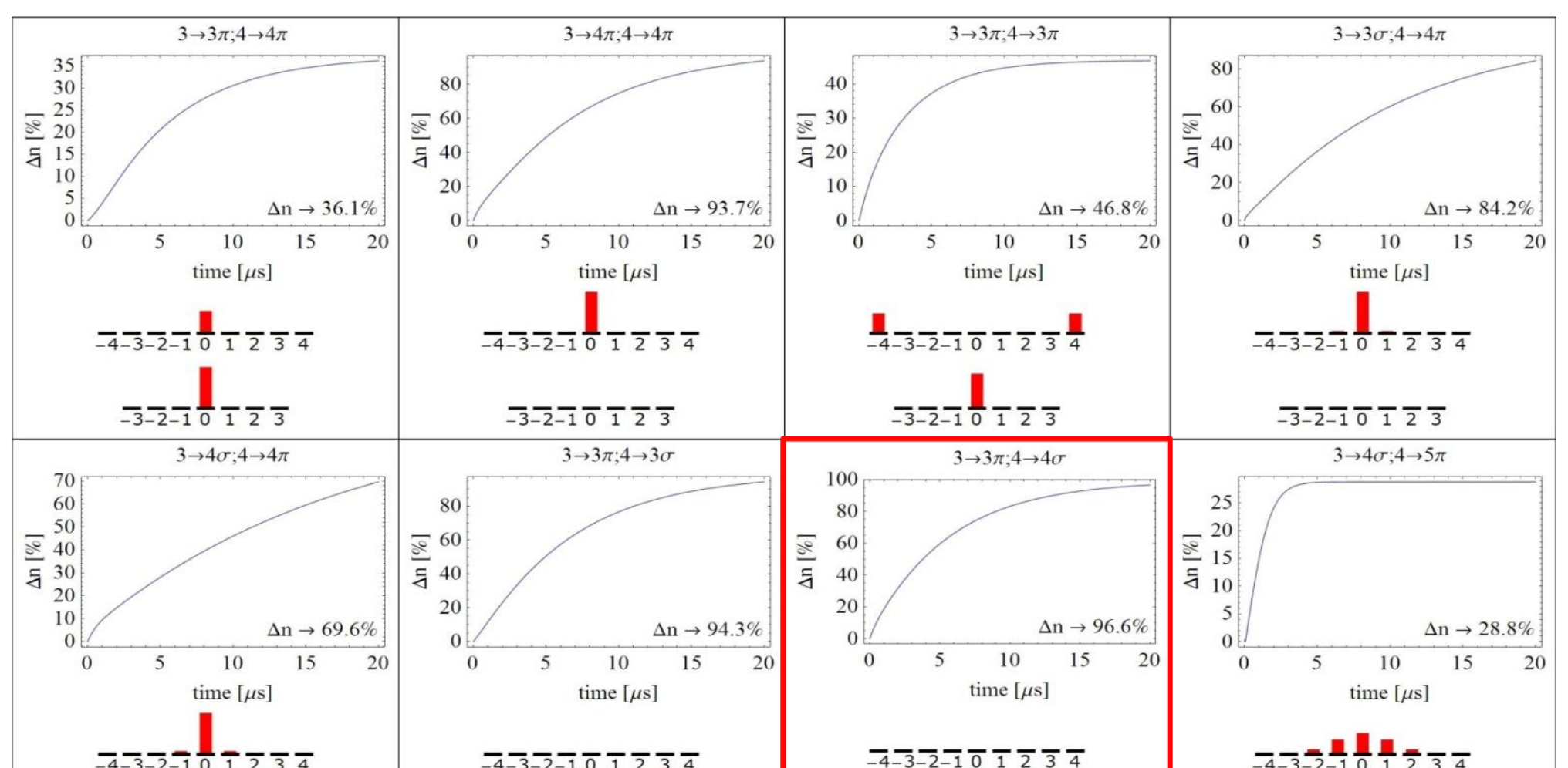
Spontaneous emission

$$A_{e_{1(2)}\to f(g)}=a_{e_{1(2)}\to f(g)}\Gamma \quad \text{with} \quad \Gamma=\frac{1}{\tau} \text{ (natural lifetime)}$$

Coupling coefficients

$$a_{F_eM_e\to F_gM_g}=(2F_e+1)(2F_g+1)(2J_e+1)\times\begin{pmatrix}F_e & 1 & F_g\\ -M_e & q & M_g\end{pmatrix}^2\begin{Bmatrix}F_e & 1 & F_g\\ J_g & 1 & J_e\end{Bmatrix}^2$$

Predictions

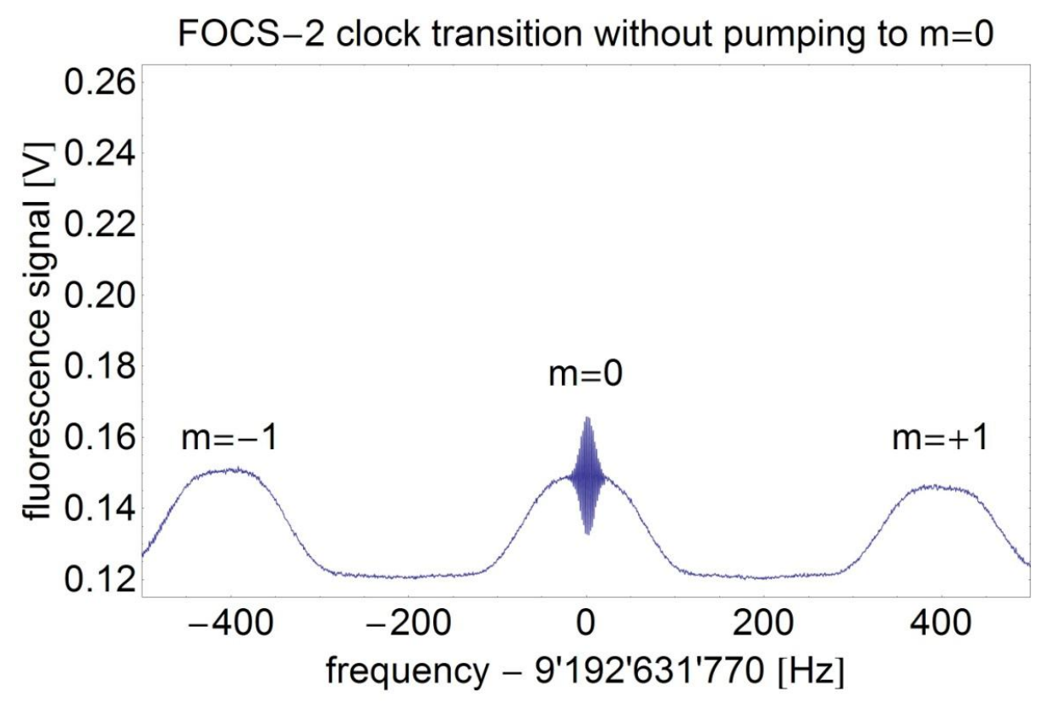


Optimal lasers parameters : F=4->F'=4 σ-polarized
F=3->F'=3 π-polarized

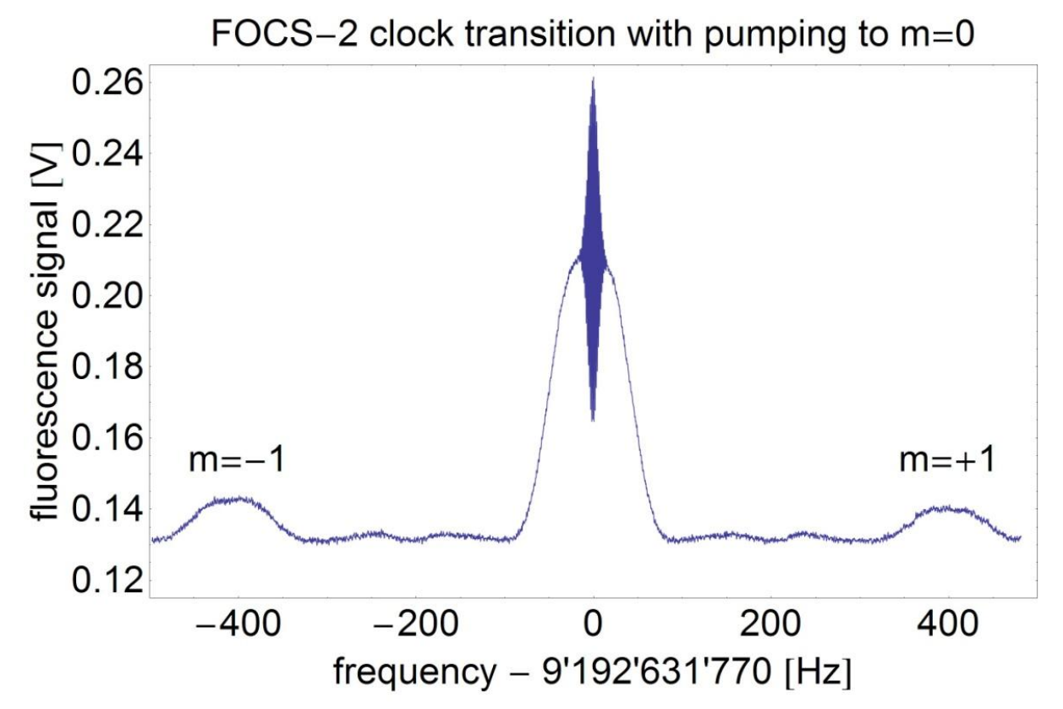
Population inversion $\Delta n=\frac{|n_{40}-n_{30}|}{n_{tot}}\xrightarrow{t\approx2ms}100\%$

Preliminary results

One laser pumping



Two lasers pumping



1. The central resonance corresponds to atoms in m=0.
2. One laser pumping results in a population distribution approximately uniform over the seven Zeeman components.
3. Two laser pumping concentrates the atoms in m=0. The distribution over Zeeman sub-levels is 80% in m=0 and 20% in m=+1,-1.
4. The useful flux is increased by a factor three.

Conclusion

We are studying quantum state preparation using laser optical pumping. Numerical simulations predict a population inversion of 98% with two lasers optical pumping. This should result in an increase of the fountain clock signal by a factor of 7, and therefore a factor √7 for the stability at the shot noise limit. Preliminary experimental results show 80% of pumping efficiency in the F=3, m_F=0 clock state.

Acknowledgments

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