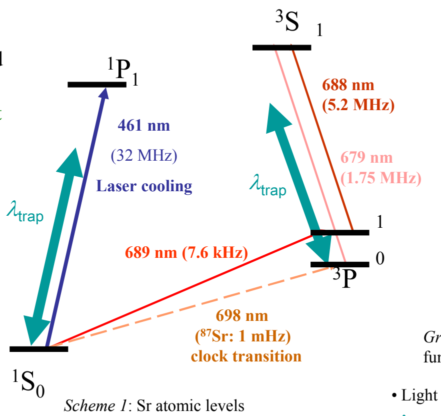
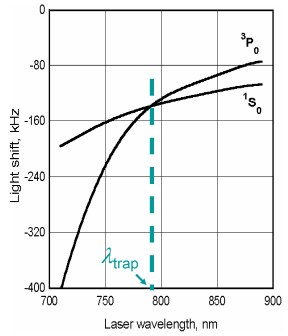
1. $^1S_0 - {}^3P_0$ line of ^{87}Sr, an attractive clock transition

- ^{87}Sr (I=9/2) : natural abundance of 7%
- $^1S_0 \to {}^3P_0$: natural linewidth of 1mHz (allowed by hyperfine coupling to $^3P_1$ and $^1P_1$ levels)
- **A neutral trapped atom clock** : Feasibility of a dipole trap with equal light shift on $^1S_0$ and $^3P_0$ states[1,2] (see Graph 1) leaving the clock frequency unchanged.
  - Possibility to combine advantages of:
    - **Trapped ions clock** : low systematic effects (Lamb-Dicke regime)
    - **Free neutral atoms clock** : high S/N ratio (large number of atoms)
  - Other advantages : weak sensitivity to the magnetic field (J=0-J=0 transition)…
- **Accuracy goal : 10^{-17}-^{18}**



Scheme 1: Sr atomic levels



Graph 1 : Light shift of $^1S_0$ and $^3P_0$ states as a function of the wavelength [2].

- Light shift cancellation **independent on polarisation**
- λ_{trap} : - far from any atomic resonance
  - powerful laser sources available

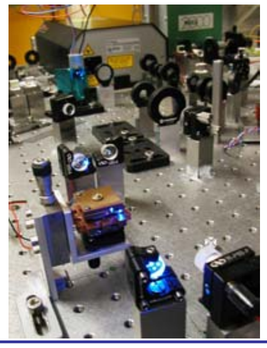
[1] H. Katori, *Proc. of 6th Symposium on frequency standards and metrology*, St Andrews 2002.

[2] V.G Pal'chikov, *J. Opt. B* **5**, S131 2003

2. Cold strontium atoms

2.1 Blue laser sources

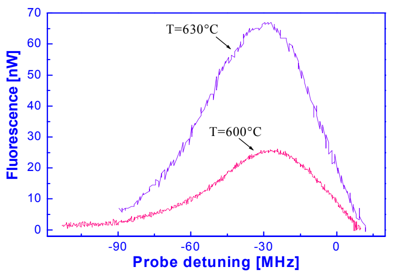
- **2000** : Generation of 461 nm light by **sum frequency mixing** in a KTP crystal (1064 nm + 813 nm) : **115 mW** is obtained
- **2003** : Generation of 461 nm light by **frequency doubling** in an intracavity PPKTP crystal with a MOPA laser @ 922 nm : **234 mW** is obtained
- Both referenced to a thermal atomic beam



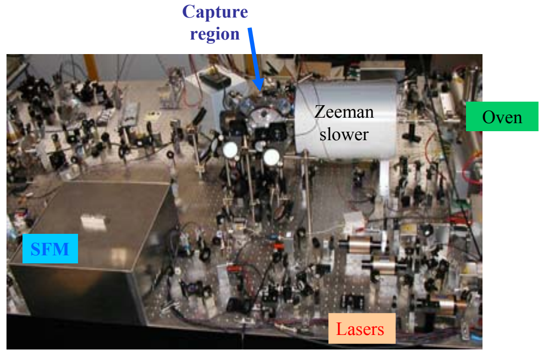
PPKTP crystal in a ring cavity

2.2 Zeeman slower

- Zeeman slower designed using **numerical simulations**:
  - Slowing laser resonant for $\omega_{laser} = \omega_{atom} - k_{laser} v - \mu_B B(z)/\hbar$
  - Optimization of the number of trapped atoms : magnetic field shape, length of the slower, laser waist and laser power.
- Magnetic coils placed inside a three layer magnetic shield :
  - Minimizes the perturbation in the MOT region
  - Creates a rapid detuning of the atoms at the slower exit



- Laser detuning : δ=-502MHz (~15.5 Γ)
- Laser power: 30 mW
- Atoms slowed to ~25 m.s^{-1}

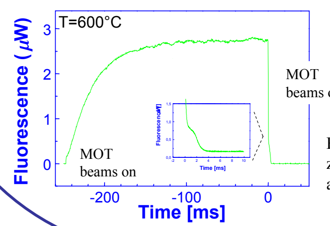


Atomic rate: ~ 10^{10} **slowed atoms/s** (oven at 630°C)

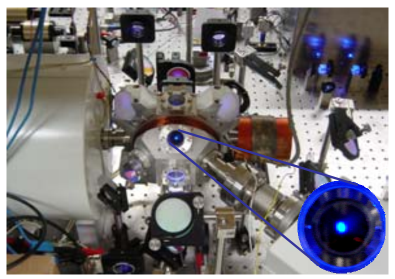
2.3 Magneto-Optical Trap (MOT)

- MOT parameters in standard operation:
  - 3 retro-reflected beams of 1cm waist radius
  - 19 G/cm gradient magnetic field
  - 17 mW of blue laser detuned by - 41MHz (-1.3 Γ)
- Slowing and trapping as efficient for ^{88}Sr, ^{87}Sr and ^{86}Sr
- **MOT life time : 50 ms**

^{88}Sr : 1.3x10^9 atoms trapped at a rate of **4x10^{10} atoms/s** (oven temperature of 630°C)



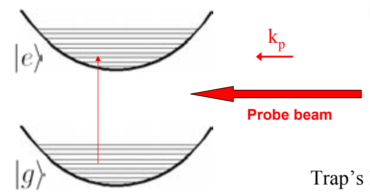
Fluorescence of the trapped atoms at T=600°C. The insert is a zoom of the fluorescence induced by the probe beam sent to the atoms after switching off the MOT beams at t=0.



Capture region. The blue spot at the window center is the cold atom cloud.

5. Lamb Dicke regime in an optical lattice

5.1 Lamb Dicke Regime



Sheme 5.1 : Two level atom trapped in an external potential, transition scheme

- Atoms confined in an external potential : $|\psi_{at}\rangle = \sum_n a_n^g e^{-i(\omega_g+\omega_n)t}|n^g\rangle + a_n^e e^{-i(\omega_e+\omega_n)t}|n^e\rangle$

$$i\hbar\frac{d|\Psi_{at}\rangle}{dt} = [H_{ext} + H_{int} + H_s]|\Psi_{at}\rangle$$ Gives the evolution of the coefficients a_n^g et a_n^e

Trap's levels quantification : $H_{ext} = \sum_n \hbar\omega_n |n\rangle\langle n|$

Internal atomic state : $H_{int} = \hbar\omega_e|e\rangle\langle e| + \hbar\omega_g|g\rangle\langle g|$

Coupling by the probe : $H_s = \frac{\hbar\Omega}{2} e^{i(\omega t - k_s x)}|g\rangle\langle e| + h.c.$

$$i\,\dot{a}_n^g = \sum_m \frac{\hbar\Omega}{2} e^{i\Delta_{m,n}t}\langle n|e^{-ik_s x}|m\rangle a_m^e$$

$$i\,\dot{a}_n^e = \sum_m \frac{\hbar\Omega^*}{2} e^{-i\Delta_{m,n}t}\langle n|e^{ik_s x}|m\rangle a_m^g$$

with :

$$\Delta_{m,n} = \omega - (\omega_e + \omega_m - \omega_g - \omega_n)$$

- Case of a strong confinement : Lamb-Dicke regime

$\langle n|e^{ik_s x}|m\rangle$ results from momentum conservation

If the spatial extension X_m of |m> is small compared to the probe wavelength, the state is highly delocalized in the p space : $\langle n|e^{ik_s x}|m\rangle \simeq \delta_{n,m}$

$$i\,\dot{a}_n^g = \frac{\hbar\Omega}{2} e^{i\delta t} a_n^e$$

$$i\,\dot{a}_n^e = \frac{\hbar\Omega^*}{2} e^{-i\delta t} a_n^g$$

$$\delta = \omega - (\omega_e - \omega_g)$$

= Rabi equations of a two level atom

=> **Internal evolution is decoupled from external degrees of freedom**

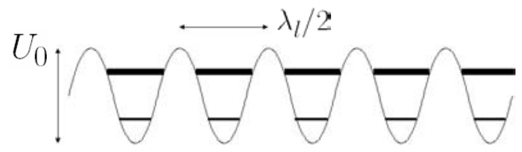
=> **No sensitivity to the recoil effect or to the Doppler effect**

5.2 Periodic potential

- Without gravity : potential from a laser (λ_l) in a standing wave configuration

$$H_{ext} = \frac{\hbar^2\kappa^2}{2m_a} + \frac{U_0}{2}(1 - \cos(2k_l x))$$

where $\hbar\kappa$ is the trapped atom impulsion, U_0 the trap's depth



Scheme 5.2 : sinusoidal potential

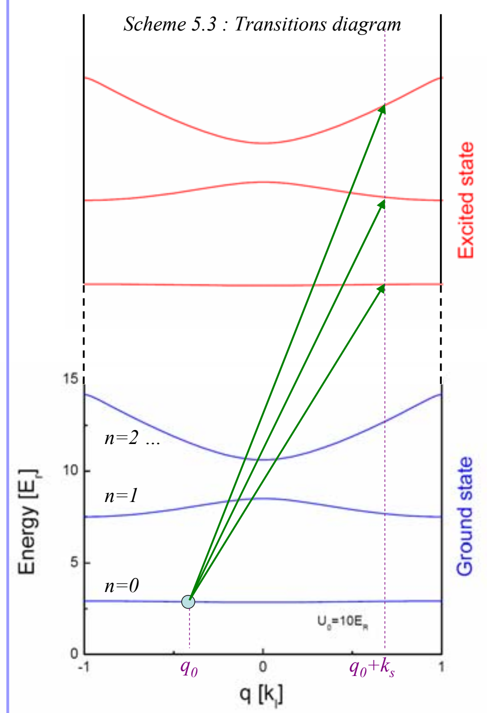
- The coupling between the infinity of wells turns the trap's levels in allowed energy bands $E_n(q)$
- Eigenstates : $|n,q\rangle$ (n = band number, q = quasi impulsion)

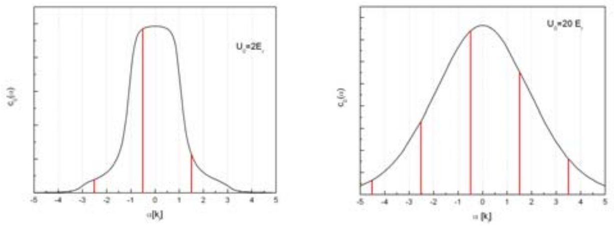
$|n, q + 2k_l\rangle = |n, q\rangle$ => q limited to the first Brillouin zone $q \in]-k_l; k_l]$

Bloch Theorem => $\langle z + \lambda_l/2|n,q\rangle = e^{iq\lambda_l/2}\langle z|n,q\rangle$

$|n,q\rangle$ is a superposition of plane waves, with increasing high order contributions at increasing U_0 (Graph 5.1 and 5.2)

$|n,q\rangle = \sum_i c_{n,\kappa_{i,q}}|\kappa_{i,q} = q + 2ik_l\rangle$ = eigenstates **delocalized all over the lattice**





Graph 5.1 (left) and 5.2 (right) : weight of the plane waves in the writing of $|n=0, q=-\frac{1}{2}k_l\rangle$ for U_0=2 E_R (left) and for U_0=20E_R

- Relevant parameter = **width of the bands**

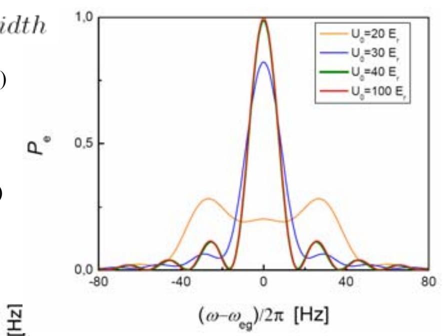
=> Case of a pure state : **shift** due to band width

(Scheme 5.3) : $\omega^0(q_0 + k_s) - \omega^0(q_0) \simeq Bandwidth$

=> Case of a superposition of states (average on the band)

$$\psi_i(t=0) = C\int_q dq|n=0,q\rangle$$

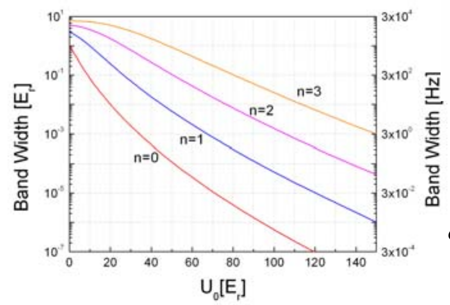
no shift, but **Q-factor limited** by the band width (Graph 5.3)



Graph 5.3 : Maximum transition probability, starting from a coherent superposition of states (Ω_{Rabi}=10 Hz)

Solution = low band width, which corresponds to a high U_0

Spectroscopy in a pure sinusoidal potential requires a deep trap depth (50-100 E_R)

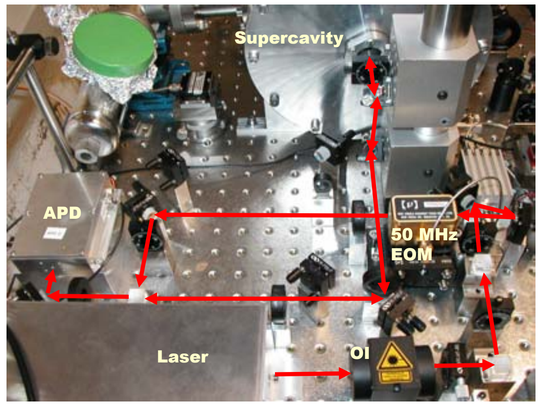


Graph 5.4 : Band width as a function of U_0

3. Red narrow linewidth laser

3.1 Feedback control

- Stabilization scheme: extended cavity laser diode locked to a high finesse Fabry-Pérot cavity (F=24 500) by the Pound-Drever-Hall method [3].



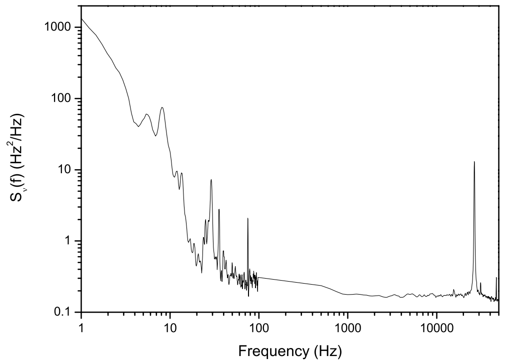
Pound Drever Hall Setup

- 100 Hz<f<20 kHz : white noise floor at 2.10^{-1} Hz²/Hz.
- f<100 Hz : mechanical vibrations.

- Sidebands at 50 MHz generated by an EOM.

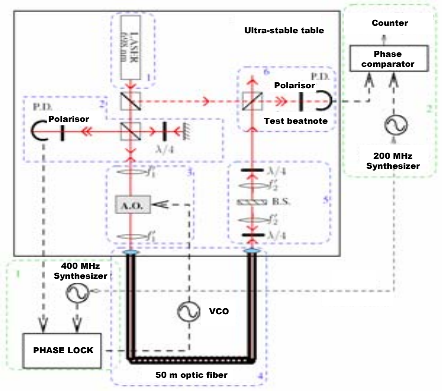
[3] R.W.P. Drever et al, *Phys. B*, **31**, 97 (1983)

- Analysis of the system performance with a second independent high finesse cavity (F=27 000). When the laser is locked to the first cavity, we collect the error signal from the second cavity which gives an estimate of the laser noise, but which is limited by the vibrations of the table of the second cavity.

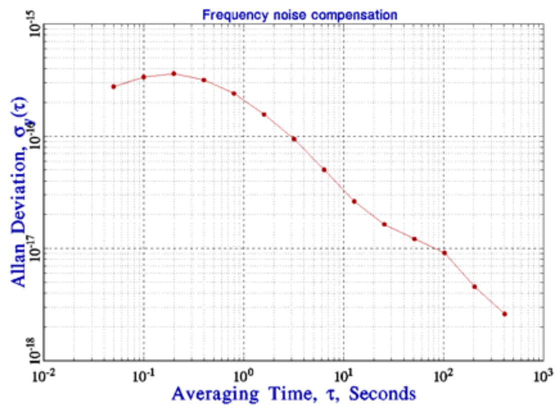


3.2 Phase-noise compensation

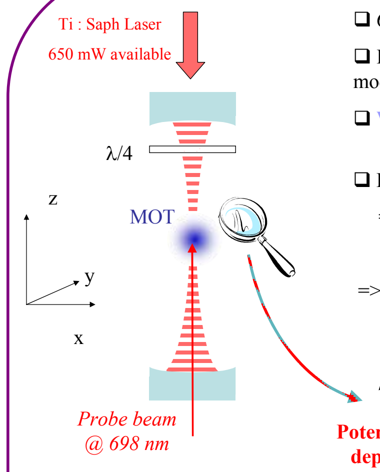
- The signal is sent to a femtosecond laser using a 50m optic fiber.
- The frequency shift due to phase noise in the fiber is compensated via an AOM controlled by a VCO.
- Frequency stability of the setup has been studied with the test beatnote

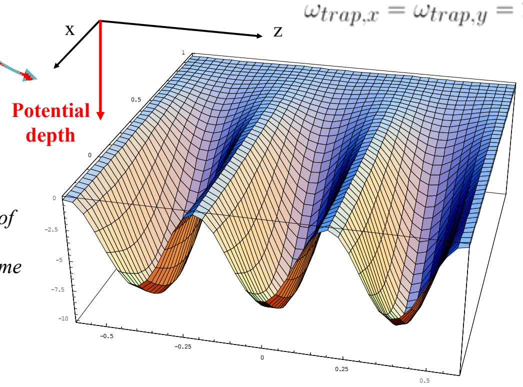


Phase-noise compensation setup



4. Dipole trap





Graph 4.1 : detailled (x,z) view of the potential at the center of the trap (the wells depths are the same on the rayleigh range ~ 6 cm)

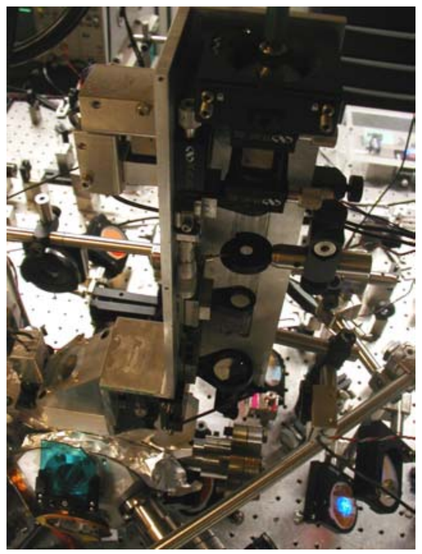
- 650 mW available @ 813 nm (magic wavelength) from a Titanium-Sapphire mode locked laser
- Enhancement linear cavity, 3 W intracavity (~ 400 Recoil Energies, E_R~3,5 kHz for the Strontium), modified Hänsch-Couillaud locking approach, to avoid heating due to modulation
- Waist = 90 µm at the center of the trap
- Red detuned trap, atoms attracted by the maximum of intensity

  => standing wave configuration along the z axis, strong confinement :

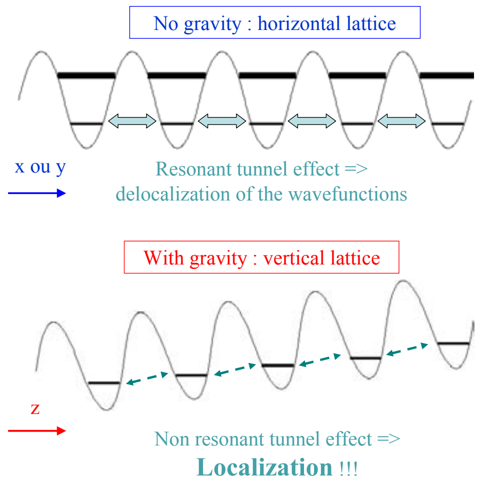
$$\omega_{trap,z} = 2\pi.140\,\mathrm{kHz}$$

=> Gaussian confinement along x and y axis :

$$\omega_{trap,x} = \omega_{trap,y} = 2\pi.300\,\mathrm{Hz}$$



5.3 Wannier Stark regime



Scheme 5.4 : Lattice and gravity

$$H_{ext} = \frac{\hbar^2\alpha^2}{2m_a} + \frac{U_0}{2}(1-\cos(2k_l x)) + m_a g x$$

$m_a g x$ couples the states $|q\rangle$

Eigenstates are $|W_n\rangle = \int_{-k_l}^{k_l} dq\, b_n(q)|q\rangle$

where

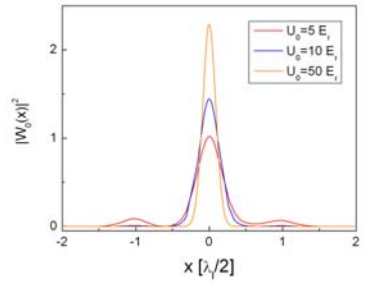
$$b_n(q) = Ce^{-\frac{i}{mg}(qE_n - \tilde{\varepsilon}(q))}$$

$$E_n = \varepsilon_0 + nmg\frac{\lambda_l}{2}$$

(ε_0 : average energy of $n=0$ band)

$$\frac{d\tilde{\varepsilon}(q)}{dq} = \varepsilon(q)$$

($\varepsilon(q)$: energy of the band as a function of q)

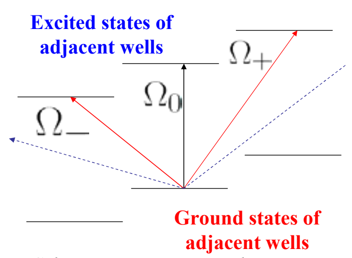


Graph 5.5 : Spatial extension of Wannier-Stark functions

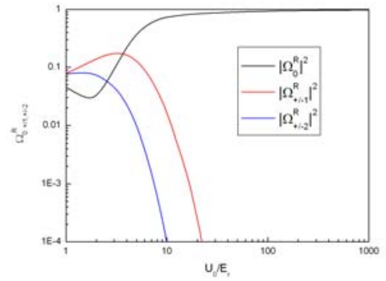
In this configuration, the wavefunctions are **very well localized**, even for a low U_0

=> Lamb Dicke regime

- Sidebands :



Scheme 5.5 : Transition diagram

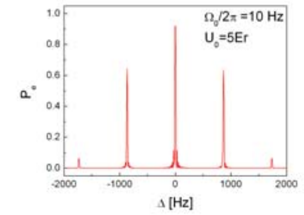


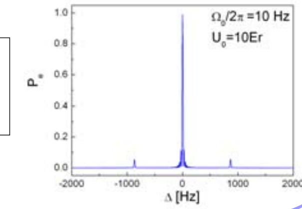
Graph 5.6 : Coupling values for the transitions ***W_0 to W_0 , W_0 to $W_{\pm1}$, W_0 to $W_{\pm2}$***

Unshifted carrier

=> Symmetric sidebands

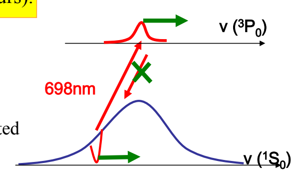
Possibility to use a much shallower potential (~ $10E_R$)



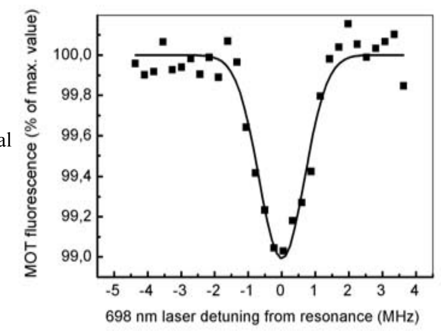


6. Direct measurement of the $^1S_0$-$^3P_0$ clock transition

- **Aim**: we want to introduce a leak to $^3P_0$ state in order to induce a detectable loss in the MOT.
- Available power @698 nm: **14 mW** sent 4 times through the MOT in a standing wave configuration.
- The corresponding Rabi frequency (w=1.3 mm) is **1.2 kHz.** As the Doppler width is **1.5 MHz** (2.3 mK), we address 10^{-3} of the trapped atoms.
- However a π-pulse duration is **0.4 ms**, 100 times smaller than the MOT lifetime. We can then accumulate atoms in the $^3P_0$ state provided the transfer rate to $^3P_0$ is constant (the dip in velocity distribution is refilled) and atoms in $^3P_0$ actually escape the trap (no stimulated photons back to the ground state).
- Pulsed experiment to avoid light-shift-> we **alternate** cooling phases (Zeeman + MOT for 3 ms) and probe phases with 698 nm laser at resonance for 1 ms. 10^6 atoms are at steady state in the MOT.
- We observe **the resonance with a contrast of 1%.**
- During the probe phases, atoms experience a Doppler detuning 10 kHz/ms due to gravity (probe laser at 45° from vertical axis). The dip in the velocity distribution induced by the excitation laser is permanently swept away. **And** atoms in the $^3P_0$ state are rapidly detuned from the excitation laser.
- **ν($^1S_0$-$^3P_0$)=429 228 004 235 (20) kHz** (measurement averaged for 2 hours).



Atomic velocity distribution in the ground and excited states during probe phases.



Experimental $^1S_0$-$^3P_0$ resonance.

7. Conclusion

Future works:

- Experimental determination of the light shift cancellation wavelength[1].
- Improvement of the dipole trap.
- Reduction of probe laser frequency noise.
- Sideband cooling ?
- Improvement of the blue source