1. $^3S_1 - ^3P_0$ line of $^{87}$Sr, an attractive clock transition

- $^{87}$Sr ($I=9/2$): natural abundance of 7%‰
- $^{87}$Sr ($I=9/2$): natural linewidth of finite (allowed by hyperfine coupling to $^1P_0$ and $^3P_0$ levels)

- A neutral trapped atom clock: Possibility 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 ion 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 (±0.0-0 transition).

Accuracy goal: 10^-18-18

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 intra-cavity PPKTP crystal with a MOPA laser (922 nm: 234 mW is obtained
- Both referenced to a thermal atomic beam

2.2 Zeeman slower

- Zeeman slower designed using numerical simulations:
  - Slowing laser resonant for $^3P_0$ states in the (1S<sub>0</sub> ↔ 3P<sub>0</sub>) clock transition
- 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

2.3 Magneto-Optical Trap (MOT)

- MOT parameters in standard operation:
  - 3 retro-reflected beams of 1 cm waist radius
  - 19 G/cm gradient magnetic field
  - 17 mW of blue laser detuned by -41MHz (1.3 fG)
- Slowing and trapping as efficient for $^{85}$Sr, $^{87}$Sr and $^{86}$Sr
- MOT life time: 50 ms

Graph 3.1: Two level atom trapped in an external potential, transition scheme

3. Red narrow linewidth laser

3.1 Feedback control

- Stabilization scheme: extended cavity laser diode locked to a high finesse Fabry-Perot cavity (F=24 500) by the Pound-Drever-Hall method [3].
- Sidebands at 50 MHz generated by an EOM.
- 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 and which is limited by vibrations of the table of the second cavity.

3.2 Phase-noise compensation

- The signal is sent to a femtosecond laser using a 69 m 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 measured with the test beatnote.

Scheme 5.4: Lattice and gravity

- Sidebands:
- Excited states of adjacent wells
- Ground states of adjacent wells

Graph 5.6: Coupling values for the transitions

Scheme 5.5: Transition diagram

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 ($\nu=\nu_{13}$) is 2 kHz. As the Doppler width is 1 MHz (2 kHz), we address 10$^4$ of the trapped atoms.
- However a pulse duration is 0.8 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).
- Polarization experiment to avoid light shift: alternate cooling phases (Zeeman + MOT for 3 ms) and probe phases with $10^6$ atoms 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.
- $\nu = \nu_{13} = 429228004235(20)$ kHz (measurement averaged for 2 hours).
- As the Doppler width is 1 MHz, we can then accumulate atoms in the $3P_0$ state.

Graph 4.3: detailed (x,z) view of the potential at the center of the trap (the wells depths are the same on the rayleigh range ~ 6 cm)

Graph 5.5: Spatial extension of Wannier-Stark functions

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

Graph 6.1: tweezer configuration

- 650 mW available @ 813 nm (magic wavelength) from a Titanium-Sapphire mode locked laser.
- Enhancement linear cavity, 3 W intracavity (~ 400 Rayleigh 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 $z$ axis, strong confinement:
  - $\omega_{trap} = 2\pi 1.10 kHz$
- Gaussian confinement along $x$ and $y$ axis:
  - $\omega_{trap,x} = \omega_{trap,y} = 2\pi 300 kHz$

Potential depth

Graph 4.1: spatial configuration

Experimental $1S_0$-$P_0$ resonance.

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

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.