Stability of the compact cold atom clock HORACE

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***Abstract*— HORACE is a compact cold cesium atom clock which is being developed in LNE-SYRTE for space applications and onboard systems. The operation of this clock is different from fountains since the laser cooling, the microwave interrogation and the detection are sequentially performed inside the spherical microwave cavity. We recently achieved short term stability of $5.5\ 10^{-13}\tau^{-0.5}$ reaching the 10^{-14} level at 3000 sec. We report in this paper recent developments and improvements, particularly on the cooling sequence. We also study the main limitations.**

I. The HORACE project

Our aim is to realize a compact atomic clock for on board systems and space operation. In terms of performances, our goal is to take benefit from laser cooling techniques to reach a short term stability in the range of 10^{-13} at 1s and an accuracy of a few 10^{-15}. We plan to operate at a high repetition rate, nearly 10 Hz, to reduce requirements on the local oscillator phase noise. The compactness of the clock physics package can be reduced to a few liters [1]. Such a cold atom clock would take advantages of microgravity operation since longer interrogation could be performed [2].

II. Experimental set up

A new experimental setup was built in summer 2005 (see fig 1). Among several technical improvements, the main motivation was to include a new detection beam. For clock operation, we must detect atomic populations by absorption directly inside the microwave cavity. Everything was done to optimize such a detection scheme on this new apparatus.

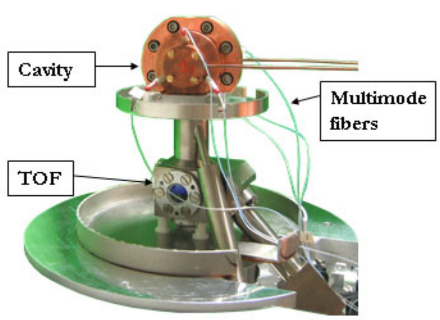

Fig. 1. Physics package without magnetic shields

As an extensive description of the experimental set up is done in [1], only a very brief overview is given here.

The physics package is made of laser-soldered Titanium. Vacuum is maintained thanks to a 2l/s ion pump at a level of 5.10^{-9}mbar. Two magnetic shields provide an attenuation of ~ 5000. A 15 mG vertical static magnetic field of is generated by a solenoid which surrounds the cavity inside the small magnetic shield.

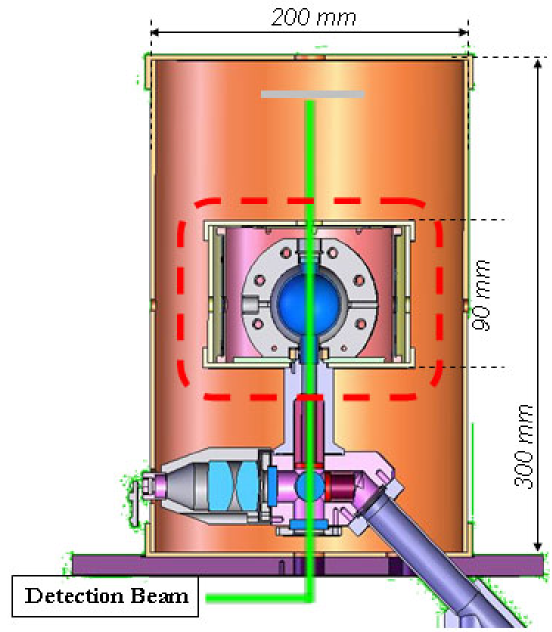

Fig. 2. Vertical cut of the whole vacuum chamber

What is specific about the HORACE clock is that all interactions, both optical and microwave, are performed at the same place, directly inside the microwave cavity.

For the need of cooling processes, this cavity is optically polished so as to reflect and scatter cooling light (it is not resonant for optical frequencies). Thus, a nearly isotropic light field is created inside and allows us to capture and cool the atoms down to a few μK. The microwave cavity acts here as a reflecting sphere for the laser field and averages power imbalances between multimodes fibers shown in fig 1.

The other purpose of this cavity is to be a microwave

[1]Size and reliability of the optical bench is also a crucial issue. Work on this aspect is studied in [3].

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resonator. It is resonant for the clock interrogation field at 9.2 GHz and surrounds a small quartz bulb which contains the Cs vapor and which is under vacuum[2]. The quality factor of the microwave resonator with the bulb is $Q \sim 3000$.

The last important part of our apparatus is the detection. The detection is done by absorption. The detection beam is shown on Fig. 2. It crosses the cavity vertically and is retroreflected by a mirror, creating a standing wave that prevents cold atoms from being heated up by absorption of the almost resonant detection beam. The photodetector is located below. . The lower part of the vacuum chamber is a time of flight detection zone used for diagnostics on cold atom velocity dispersion and will be removed in the next version of the experiment.

III. Typical clock sequence

Each interaction is performed sequentially inside the microwave cavity. A typical clock timing is divided in 3 parts : cooling, interrogation and detection. The first part consists in capturing the atoms from a cesium vapor using the $|F=4\rangle \rightarrow |F=5'\rangle$ cycling transition and a repumping beam. Then, the cooling light is switched off and the atoms are optically pumped in the $|F=3\rangle$ level. For the moment there's no Zeeman-substates selection. The next step consists in performing the microwave Ramsey Interrogation on the $|F=3, m_f=0\rangle \rightarrow |F=4, m_f=0\rangle$ transition. Then, we detect the atomic populations of both clock states in order to calculate the probability of transition. This is done using a vertical linear absorption beam through the atomic sample. Finally, the frequency correction is sent to our DDS which provide a nearly 7368230 Hz signal (9.2GHz - 9.192631770 Hz). The frequency instability is thus derived by plotting the allan deviation of these frequency corrections.

	Duration
Cooling	110 ms
Pumping	1 ms
Interrogation	1 ms + 50 ms +1 ms
Detection	10 ms
TOTAL	**~173 ms**

TABLE I
Typical operation sequence

IV. Cooling Sequence

A. Goals of the cooling Sequence

The efficiency of the cooling sequence is a key point for a cold atom clock like HORACE. The goals of the cooling stage is to produce the largest number of cold atoms in the shortest time. As it can be seen in (1) one would like to increase the number of cold atoms contributing to the clock signal (ie the SNR). This essentially depends on the cooling duration T_{cool}. But one cannot perform a too long cooling sequence so as not to increase sensitivity to the local oscillator phase noise (Dick effect). An extensive and quantitative study of this trade off is done in [2].

$$\sigma_y(\tau) = \frac{1}{\pi}\frac{\Delta\nu}{\nu_{Cs}}\frac{1}{SNR_{1shot}}\sqrt{\frac{T_{cycle}}{\tau}} \qquad (1)$$

where T_{cycle} = T_{cool} + T_{int} + T_{det}.

B. Optimizing the cooling sequence with a blue-detuned pulse

Fig.3 represents the laser intensity used during cooling phase. The cooling parameters are given in table II.

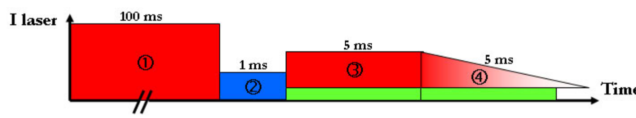

Fig. 3. Cooling sequence : Laser intensity as a function of time

	Duration	**Power**	**Detuning**
① Doppler	110 ms	40 mW	-2Γ
② Blue pulse	1 ms	3 mW	$+\Gamma/2$
③ Capture	1ms	5 mW	-3.5Γ
④ Sisyphus	10 ms	5 mW $\rightarrow$ 0 mW	$-3.5\Gamma \rightarrow -12\Gamma$
Detection beam	7 ms	100 μW ($I = I_{sat}/2$)	$-\Gamma/4$
TOTAL	**~173 ms**		

TABLE II
Typical cooling sequence parameters

The sequence begins with a so called "Doppler" phase ① with maximum intensity and slightly red detuned light. At the end of this phase, it seems that most of the cold atoms are out of the detection axis. We think this is a direct consequence of light losses along this axis, due to the holes for the detection beam ($\phi = 12mm$). Actually we have good reasons to think that the cold atom cloud has the shape shown in fig 4, with two lobes.

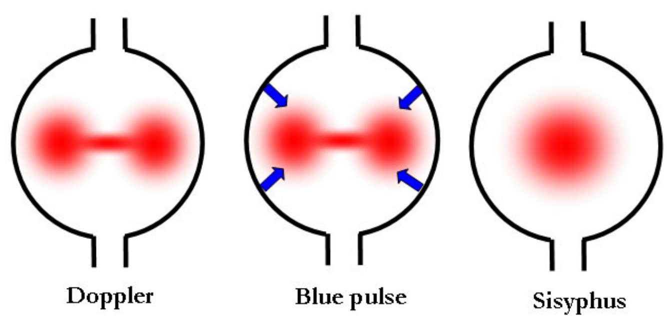

Fig. 4. Evolution of cold atom cloud shape during cooling sequence

Obviously we wandered how could we save all these atoms back. Is it possible to gather all these cold atoms to the center to use them for clock operation ?

[2]This bulb is here only for experimental reasons. It prevents interactions between Cs vapor and copper. In the next experiment, the cavity will be under vacuum and coated to prevent such interactions

To do this we use a little trick which is very unusual with cold atoms. First we send to the atoms a small pulse of blue-detuned light ②. Doing this we transfer them a little "kick"[3] so as to push them back to the center. Then, when most of cold atoms cross the center of the cavity, we capture them by tuning the cooling light back to the red ③. The laser parameters of the "blue" pulse are chosen so that atoms velocity remains below the capture velocity of the "capture" pulse. Finally, we cool the atoms down to several μK using "Sisyphus like"[4] cooling which is easily realized by ramping down to zero the intensity and by increasing the detuning of the laser ④. During these last 2 steps (3 & 4) we superimpose to the isotropic light the detection beam. Although this beam is not optimized for cooling it greatly improves the efficiency of the capture process mentioned above (see in Tab.III). Tab.III compares the detected signal for different cooling sequences we used successively.

Sequences Total cooling time is constant	**Detected signal** in relative absorption
Doppler	1
Doppler + Sisyphus	4
Doppler + Sisyphus + Det. beam	8
Doppler + Sisyphus + Det. beam + blue pulse	24

TABLE III

COMPARISON BETWEEN DIFFERENT COOLING SEQUENCES.

This optimized scheme allowed us to reduce cooling time down to 110 ms for 10^8 cold atoms (all Zeeman sublevels, T°= 5μK).

V. DETECTION SEQUENCE

It must be recalled that detection is done by absorption directly inside the microwave cavity. These detection scheme is necessary for us to improve cyclic ratio. We do not want to wait for the atomic free fall time in the TOF detection zone. Moreover, HORACE is designed for space applications and TOF detection would be impossible in a microgravity environment as atoms are not launched (like in the PHARAO clock).

Our detection sequence allows to normalize the transition probability and is schematically represented on Fig.5. It uses optical and microwave[5] pulses. We measure the absorption level of each clock state population called N_3 and N_4, then we subtract the baseline given by the thermal background vapor absorption. The difference between those two levels gives the contribution of cold atoms only.

We encounter several difficulties with this kind of detection scheme. First, we have a very small useful signal because nearly 99.5% of detected intensity is direct background from laser. Our absorption signal per population in typical operation is about 30 mV. Moreover, we are also very sensitive to any laser fluctuations (frequency and intensity). Our detection pulses are very short, about 1 ms, which doesn't allow low frequency noise (50-60 Hz) to be averaged. Furthermore, thermal vapor and retroreflected configuration creates a saturated absorption scheme which demodulates frequency fluctuations of the laser. Actually, this frequency noise sets a limitation to the "shot to shot" SNR between 270 ($\Delta\nu = -\Gamma/2$) and 400 ($\Delta\nu = 0$)[6]. Unfortunately, during clock operation (ie with cold atoms) SNR do not exceed 250. There is a critical trade off with the laser detuning between sensitivity to frequency fluctuations (max sensitivity when $\Delta\nu = -\Gamma/2$, min sensitivity when $\Delta\nu = 0$) and heating of cold atomic samples which degrades normalization (min heating when $\Delta\nu = -\Gamma/2$, max heating when $\Delta\nu = 0$).

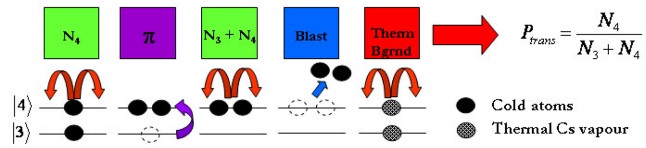

Fig. 5. Detection sequence

VI. STABILITY

We measured a frequency stability for the first time with HORACE in January. The first measurements led to $\sigma_y(\tau) = 4.10^{-12}\tau^{-0.5}$ and mainly thanks to the major improvements on the cooling sequence we reach a short term stability of $\sigma_y(\tau) = 5.5\ 10^{-13}\tau^{-0.5}$ (see fig 6). It nearly reaches the 10^{-14} level at 3000s. Our typical operation parameters are summarized in Tab.IV.

Repetition rate	6 Hz
Linewidth	10 Hz
Cyclic Ratio	0.3
Detected atoms	10^7
SNR "shot to shot"	250
Local oscillator	H-maser

TABLE IV

TYPICAL OPERATION PARAMETERS

VII. LIMITATIONS

A. *Short term stability limitations*

Our goal is to reach a short term stability of a few 10^{-13} at 1s. Table V gives the main noise sources and their respective contributions. The most significant noise comes from detection.

Acquisition and electrical noises are essentially technical issues and could be reduced using low noise electronic devices.

[3]The way we figured it out is purely phenomenological, for the moment there's no simulations describing this.

[4]Sisyphus cooling stands on polarization gradients whereas here with isotropic cooling scheme polarization is not defined due to reflections and scattering on the cavity walls.

[5]We can perform microwave π pulse because atoms remain in the microwave cavity. We can't use optical pumping because many atoms remain in $|F = 3, mf \neq 0\rangle$ states after the interrogation

[6]These limitations were evaluated with a given value of the signal (ie 30 mV) and by recording the noise when the clock is operated on the thermal vapor only

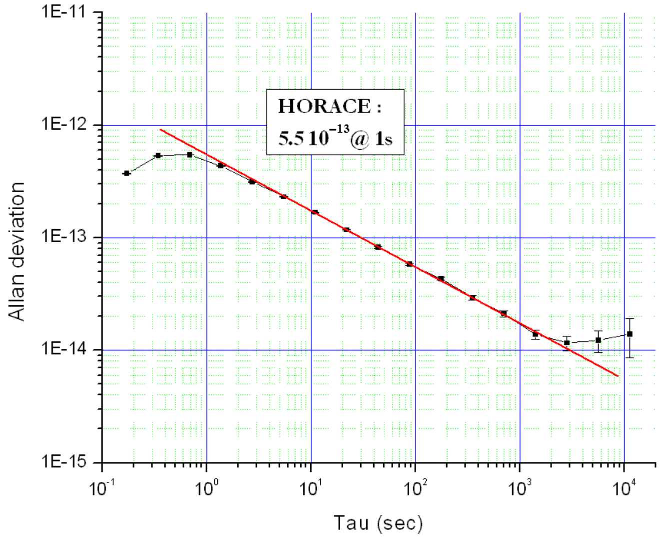

Fig. 6. HORACE frequency stability

Noise sources	Contribution to stability @ 1s
Acquisition & Electrical noise	3.2 10^{-13}
Laser intensity noise	1.6 10^{-13}
Laser frequency noise	3.3 10^{-13}
Microwave noise	2.5 10^{-13}
Quantum projection noise	5 10^{-14}
TOTAL	5.5 10^{-13}

TABLE V
SHORT TERM STABILITY NOISE BUDGET

Intensity noise contribution has been reduced to 1.6 10^{-13} by normalizing power fluctuations with another photodetector during detection pulses. It might be further reduced by locking laser power. Laser frequency noise should be reduced using a faster modulation in our frequency locking scheme, leading to a larger locking bandwidth. The microwave noise (Dick effect) can be decrease to the 10^{-13} level or below with an optimized (and realistic) oscillator for our repetition rate. [7].

B. Mid term stability limitations

Concerning mid term stability our goal is to reach the 10^{-15} range. For the moment we don't have explanation for our limitation at the 10^{-14} level. Many systematic effects can degrade stability when they are not controlled. The study of these effects for the accuracy budget of the clock would allow us to improve mid term and long term stability. We've only checked that magnetic field fluctuations was not limiting (around 10^{-15}).
Main hypothesis are :

Cold collisions : We expect the effect of cold collisions to be much bigger than in atomic fountain since there's no zeeman selection process. Cold atoms remain in all $|F = 3, m_f \neq 0\rangle$ states during the interrogation. For the moment there's no active control on the cold atom number fluctuations (below 1% up to 10^4 s). Moreover, use of multimodes fibers (sensitive to temperature) may lead to density and shape fluctuations in the cold atom cloud.

Cavity pulling : It depends on cold atom number fluctuations as well and on cavity tuning (ie thermal fluctuations). As the atoms stay inside the microwave cavity during all the interrogation it should have a big influence.

Microwave switch induced phase noise : We'll have to check the phase noise due to the microwave switch. The atoms see all phase transients and microwave mode installation as they remain in the cavity. We switch the interrogation field at 9.192.. GHz directly and according to ref [4] it is better to switch the RF field before mixing with the 9.2 GHz.

VIII. CONCLUSION & PERSPECTIVES

With short term stability of 5.5 $10^{-13}\tau^{-0.5}$ we demonstrated that the HORACE cold atom clock can reach performances better than compact Rb clock and thermal Cs beam. These results are very encouraging as our current limitations are essentially technical issues. We are very confident in reaching short term stability of 2-3 10^{13} within few months. Next steps our work will be to improve mid term stability and evaluate accuracy.

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[7] We use currently an H-Maser as local oscillator