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$3 \cdot 10^{-12} \cdot \tau^{-1/2}$ ON INDUSTRIAL PROTOTYPE OPTICALLY PUMPED CESIUM BEAM FREQUENCY STANDARD

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***Abstract* - The GALILEO European Global Positioning program requires very stable clocks either for space or ground applications. This paper describes the short-term stability improvement study on an industrial prototype developed by TEKELEC SYSTEMES. This study has been performed with the scientific support from SYRTE and the financial support from DGA/CELAR.**

The prototype is designed to reach one of the industrial goals: small sized sealed tube and compact optical bench rigidly fixed along it. In this paper we focus on the optical device using two laser wavelengths in order to improve the clock frequency stability: the 4-4 pumping transition of the cesium D_2 line for the atomic preparation and the 4-5 cycling transition for the atomic detection.

The experimental results reported in this paper show that the atomic detection with an optical cycling transition improves the frequency stability by a factor 3 to 6 compared to the basic scheme using the same optical pumping transition for both preparation and detection purposes. This high performance level is reached with a low atomic flux consistent with a ten-year lifetime and a commercial DBR diode laser having a spectral linewidth as high as 3 MHz.

***Keywords* - Atomic frequency standard, Compact clock, Cycling transition**

I. INTRODUCTION

TEKELEC SYSTEMES has been developing industrial prototypes of optically pumped cesium beam frequency standard for 10 years [1]. These developments have been supported by the French military administration (DGA/CELAR) and are based on years of work performed by the "Laboratoire de l'Horloge Atomique" (LHA, now part of the SYRTE) [2 ; 3].

The European Global Positioning System program "GALILEO" requires compact atomic clock with a very good short-term stability ($\sigma_y(\tau) \leq 3 \cdot 10^{-12} \cdot \tau^{-1/2}$).

First TEKELEC SYSTEMES developments were not focused on this level of short-term stability. The best results obtained on our industrial prototypes with compact sealed tube were in the range of $\sigma_y(\tau) \cong 8 \cdot 10^{-12} \cdot \tau^{-1/2}$ with a low cesium flux consistent with long lifetime, more than 10 years with 3 g of cesium. The aim of this study is to demonstrate the short-term stability improvement by just modifying the optical system, without any action on the tube itself or on the cesium beam intensity.

The final measurements have been performed against a hydrogen maser lent by the CELAR.

II. GENERAL PRINCIPLES

The cesium atomic structure is presented figure 1. The definition of the second is based on the frequency difference between the two hyperfine levels (F=3 and F=4) of the ground state ($6^2S_{1/2}$). Figure 1 shows the two first levels ($6^2P_{1/2}$ and $6^2P_{3/2}$), which can be excited by two wavelengths (D1 and D2 lines). A laser diode performs optical pumping and detection by exciting the cesium atom. The full lines represent the excitation transitions allowed by the selection rules ($\Delta F=0, \pm 1$). The dashed lines give the recombination transitions following the same rules.

In this scheme, the green arrows correspond to pumping transitions and the red ones to cycling transitions.

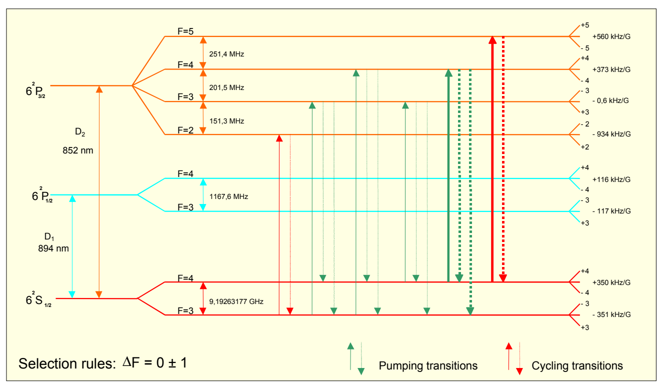

Fig. 1. Atomic structure of the cesium.

Considering the D_2 line, the transitions from the F=3 or F=4 hyperfine levels of the ground state to the F'=3 and F'=4 hyperfine level of the excited level are pumping transitions. Because the excited atom can recombine either on the F=3 or the F=4 level of the ground state.

The transition between the level F=3 of the ground state to the level F'=2 of the excited state or from the level F=4 of the ground state to the level F'=5 of the excited state are cycling transitions. Since the atoms can only recombine on the original level.

A cesium tube is a resonator in which the resonance is determined by the population of the two hyperfine levels of the ground state of the cesium atom ($6^2S_{1/2}$ state in fig. 1). In the preparation zone the beam is prepared to populate only the same hyperfine level (F=3 or F=4). In the next interaction zone, a microwave is applied to induce recombination between the two hyperfine levels if the frequency is fitted with the atomic transition. In the clock signal detection zone we analyze the atoms in the level emptied in the preparation zone.

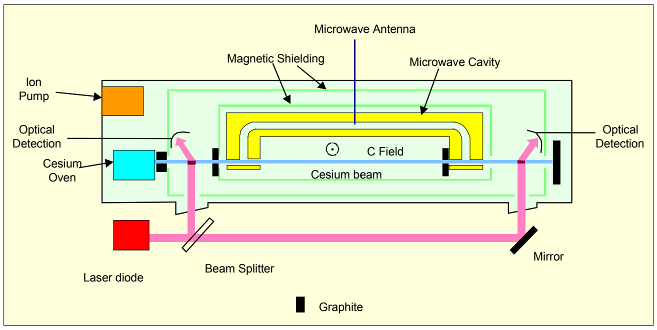

Fig. 2. Conventional tube of Optically pumped cesium beam frequency standard.

In an optically pumped cesium beam frequency standard atomic preparation and clock signal detection are performed by optical excitation.
In a conventional optically pumped cesium tube, as shown fig. 2, preparation and detection use the same wavelength from the same diode laser. The diode laser is locked on the right transition by using the fluorescence signal detected by a photodiode in the preparation zone. The use of a pumping transition is mandatory in that case to perform the preparation.

The optical structure is very simple and the detection signal is limited by the pumping effect to 4 photons per atom approximately. If we can use a cycling transition for the detection this limitation does not exist and the number of photon per atom can be multiplied by at least 15.

III. SIGNAL TO NOISE RATIO

The short-term stability of an atomic clock is described by the equation:

$$\sigma_y(\tau) = \frac{A}{Q \cdot (S/N)} \cdot \tau^{-1/2} \qquad (1)$$

Where Q is the quality factor of the atomic line
S/N is the signal to noise ratio
τ is the sample time

Increasing the signal to noise ratio will improve the short-term stability of the clock. Using a cycling transition will increase the signal, but it is important to analyze the effects on the noise.

There are several sources of noise that can affect the signal to noise ratio. In our first approach we have not taken into account the contribution of the laser diode noise because its influence is low in the case of using a pumping transition (3-3). However this contribution could be important with a cycling transition (4-5), a complementary study needs to be performed to analyze it.
Except the laser noise, the main noise sources can be presented very roughly as a first approach to obtain orders of magnitude by:

- The shot noise I_{sn}, which is due to atom fluctuations described by a Poisson distribution. The noise varies with the square root of the atomic flux and thus of the current in the detector I_0:

$$\overline{I_{sn}^2} = 2 \cdot q \cdot I_0 \cdot B_n \qquad (2)$$

where q is the charge of the electron and
B_n is the noise bandwidth.

- The Johnson noise I_{jn} is related to the carrier thermal agitation, which appears in all resistance. Its value is given by:

$$\overline{I_{jn}^2} = \frac{4 \cdot k \cdot T \cdot B_n}{R} \qquad (3)$$

where k is the Boltzman constant,
T is the temperature and
R the resistance.

- The detector noise is the product of the Noise Equivalent Power (NEP) of the photo-detector ($1.5 \cdot 10^{-14}$ W/$\sqrt{\text{Hz}}$ in our case) by the photo detector sensitivity (0.55 W/A in our case).

- The stray light noise I_{sln} is related to the ratio of the stray light level to the detection signal R_{sl}. It can be expressed by:

$$\overline{I_{sln}^2} = \overline{I_{sn}^2} \cdot R_{sl} \qquad (4)$$

The resulting noise is the quadratic sum of these individual noises. The following table shows the values of these noise in our industrial prototype and their contributions to the signal to noise ratio. These values have been obtained with a 3-3 pumping transition for both atomic preparation and signal detection. The signal amplitude is 0.104 nA.

	Noise Value (fA/√Hz)	Signal to noise contribution
Shot noise	4.1	25 400
Johnson noise	9.1	11 400
Detector noise	8.3	12 500
Stray light noise	18.8	5 500
Total noise	22.8	4 500

Table 1. Noise evaluation and signal to noise contributions when using 3-3 transition for preparation and detection

Signals to noise contributions in the tables are just given as calculation elements.
The high stray light noise is partly due to a poor optical quality of the window.

The shot noise is proportional to the signal. Its contribution to the signal to noise ratio represents the theoretical limit of the signal to noise ratio of the clock with this cesium beam intensity.

The next figure shows the Allan deviation of the industrial prototype in the same conditions against a HP5071A with option 001, which contributes to the stability measurement too.

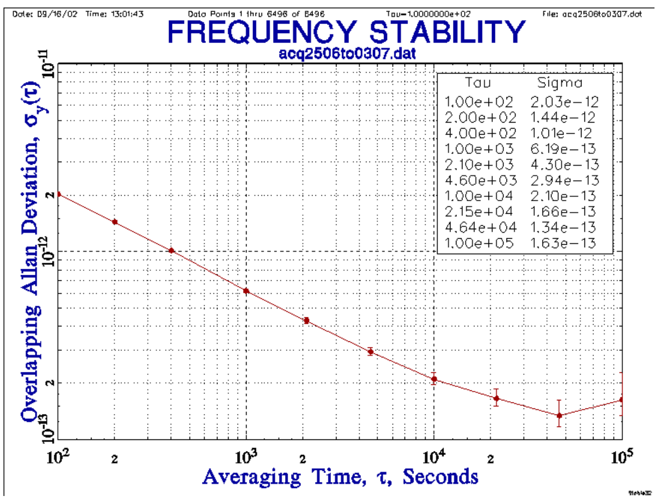

Fig. 3. Allan deviation on the industrial prototype (3-3 transition for both optical zones) against a HP5071A option 001 clock.

IV. PROTOTYPE DESIGN

In order to improve the clock short-term stability we decided to use a cycling transition for the detection. The simplest way to use a pumping transition in the preparation zone and a cycling transition in the detection zone is to shift the diode laser wavelength between the two zones by an acousto-optic modulator. In that case there are two couples of transition possible 3-3 and 3-2 or 4-4 and 4-5. The best cycling transition is the 4-5, it is why we changed the pumping transition to use the 4-4 one.
We wanted to build a very compact demonstrator, so we decided to keep locking the diode laser directly on the beam itself using the fluorescence signal detected by a photodiode in the preparation zone, and not on an external cesium cell as it is done in most laboratory designs [4].

The first step of this study was to demonstrate the feasibility of locking the diode laser frequency on the cesium atom 4-4 transition.

Our electronic system automatically finds the right transition and locks the diode laser on it. Special embedded software allows the system to relock in less than half second in case of trouble, which does not affect the clock stability.

The figure 4 shows the Allan deviation obtained with the 4-4 transition for both optical interactions. As expected theoretically the stability is slightly degraded but the very good behavior during several days fully demonstrates the feasibility of locking the diode laser directly on the 4-4 transition of the beam.

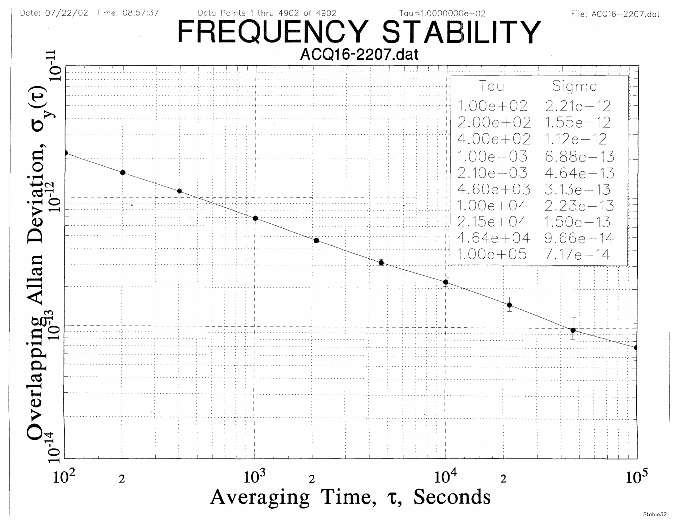

Fig. 4. Allan deviation on the industrial prototype (4-4 transition for both optical zones) against a HP5071A option 001 clock.

The figure 5 shows the modifications of the optical bench. The first part of the bench was kept mostly unchanged.

After the beam splitter we have added a lens to focalize the laser beam in the acousto-optic modulator. The acousto-optic modulator shifts the light by 251 MHz. The two sets of Glan Taylor polarizer and half wavelength plate adjust the right polarization and the signal power in each zone.

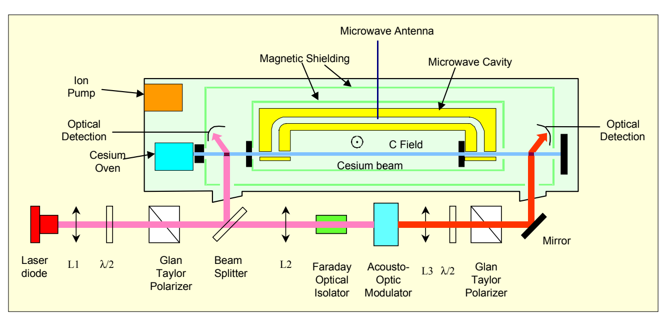

Fig. 5. Modification of the optical bench.

The next photograph shows the tube and the new optical bench rigidly fixed along it. The tube is less than 40 cm long.

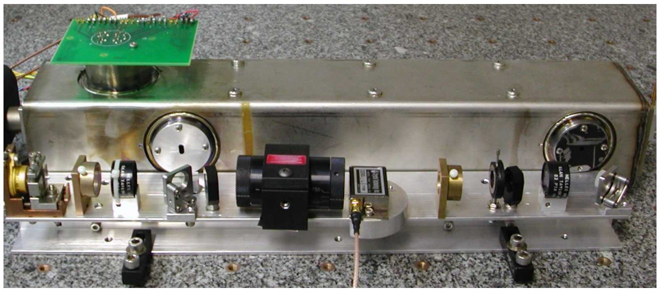

Fig. 6. View of the tube and the optical bench.

The 35 dB Faraday optical isolator is necessary to remove the feed back from the array of the acousto-optic modulator. We believe that with a special design of this modulator we can remove the isolator, which is the bigger and the most expensive element of the optical bench.

The diode laser used in this study is Diffracted Bragg Reflector type (DBR) from SDL manufacturer. This diode laser has a line width as high as 3 MHz.

V. IMPROVEMENT OF THE S/N RATIO

To set the optical bench, we have tested the signal to noise ratio in order to find the best conditions (optical power in each zones…).
In fact the optical power in the detection zone was not set at the optimal value due to optical bench limitations. In these conditions, the signal value is 1.70 nA.
The next table shows the new values of each noise source and their calculated contribution on the signal to noise ratio.
Even though the signal is improved by a factor 17, the contribution of the shot noise on the signal to noise ratio is unchanged since this noise is proportional to the signal. This noise becomes the main one.
The Johnson noise and the detector noise are unchanged so their contributions to the signal to noise ratio become negligible.
The stray light noise is increased but much less than the signal so the contribution to the signal to noise ratio is nearly three times lower. Nevertheless this contribution is not negligible since it generates a reduction of the signal to noise ratio of nearly 10 %.

	Noise Value (fA/√Hz)	Signal to noise contribution
Shot noise	66.9	25 400
Johnson noise	9.1	187 000
Detector noise	8.3	205 000
Stray light noise	25.3	67 000
Total noise	72.6	23 400

Table 2. Noise evaluation and signal to noise contributions when using 4-4 transition for preparation and 4-5 for detection

VI. STABILITY MEASUREMENT

The stability measurements were performed against an active hydrogen maser lent for a period of four weeks by the CELAR laboratory belonging to the French Military Administration,.

The figure 7 shows the Allan deviation measured against this maser.

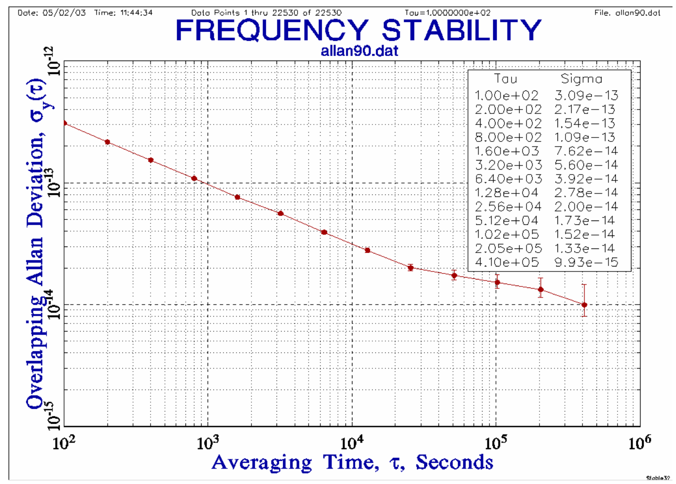

Fig. 7. Allan deviation on the industrial prototype (4-4 and 4-5 transition) against a H Maser.

The clock exhibits a short-term stability of $\sigma_y(\tau) \cong 3 \cdot 10^{-12} \cdot \tau^{-1/2}$. The four week measurements is not long enough to evaluate the flicker floor value but simulations allow us to estimate it at a level less than $1 \cdot 10^{-14}$.

VII. IMPROVEMENT PERSPECTIVES

There are several sources of improvements for the clock performances.
First, the bench can be improved in order to increase the signal in the detection zone, since the tests we have processed show that the signal to noise optimum ratio was not reached yet.
Second source of improvement is related to diode laser. We have used a diode laser having a high line-width (3 MHz). We believe that with a DBR diode laser from Yokogawa with a line-width of less than 1 MHz or with an Extended Cavity Laser (ECL) we can further reduce the laser frequency and the stray light noise and so improve the signal to noise ratio and thus the stability.

We have kept a low beam intensity in order to maintain a high lifetime of our tube. It is possible to improve the stability by increasing this intensity. It is possible in that conditions to maintain a high lifetime by increasing the size of the cesium oven and the quantity of graphite in our tube, which are the only elements of the tube that limit the life time in an optically pumped tube.

We believe that stability in the range of $\sigma_y(\tau) \approx 1 \cdot 10^{-12} \cdot \tau^{-1/2}$ is a reachable goal.

Furthermore we believe that with a special design of the acousto-optic modulator we can remove the Faraday optical isolator. This will simplify the optical bench and reduce its size.

VIII. CONCLUSION

We have demonstrated a short stability of $\sigma_y(\tau) \cong 3 \cdot 10^{-12} \cdot \tau^{-1/2}$ on an industrial prototype of compact optically pumped cesium beam frequency standard. This excellent result has been obtained just by modifying the optical bench. Significant perspectives of improvements have been identified.

These results along with improvement capabilities make optically pumped cesium a well suited technology to built high stability clocks for the European Global Navigation Satellite System GALILEO, both for space and ground segments.

IX. ACKNOLEGEMENT

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X. REFERENCES

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