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PHARAO SPACE ATOMIC CLOCK: NEW DEVELOPMENTS ON THE LASER SOURCE

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Abstract:

The PHARAO project purpose is to open the way for a new atomic clock generation in space, where laser cooling techniques and microgravity allow high frequency stability and accuracy.

The French space agency, CNES is funding and managing the clock construction. The French SYRTE and LKB laboratories are scientific and technical advisers for the clock requirements and the follow-up of subsystem development in industrial companies.

EADS SODERN is developing two main sub-systems of the PHARAO clock: the Laser Source and the Cesium Tube where atoms are cooled, launched, selected and detected by laser beams. The Laser Source includes an optical bench and electronic devices to generate the laser beams required.

This paper describes PHARAO and the role laser beams play in its principle of operation. Then we present the Laser Source design, the technologies involved, and the status of development. Lastly, we focus of a key equipment to reach the performances expected, which is the Extended Cavity Laser Diode.

1 INTRODUCTION :

The Cesium space atomic clock PHARAO is developed by CNES (French National Center for Space Studies) in order to be the first laser cooled atomic clock in space [1].

This clock will be the heart of the ACES (Atomic Clock Ensemble in Space) ESA (European Space Agency) payload on ISS (International Space Station) which purpose is to do some experiments on cold atom physics in conditions that are not accessible on Earth.

Its design is based on the works of two French laboratories, SYRTE (SYstème de Référence Temps-Espace, previously called Laboratoire Primaire du Temps et des Fréquences) and Kastler-Brossel Laboratory, on atomic fountains using laser cooling of Cesium atoms and effects of microgravity [2], [3]. These laboratories realized among the currently world's most accurate atomic clocks.

French industrial companies are integrating the Engineering Models of the space clock subsystems. The whole clock Engineering Model will be integrated and tested, by CNES, with technical and scientific advises from the French laboratories involved.

The high level of performances that PHARAO aims to reach (accuracy of 10^{-16} and frequency stability between 10^{-16}-10^{-17}/day) implies different optical interactions between atoms and laser beams. These interactions occur before and after the microwave ones used to compare the microwave source frequency to the atomic reference. They allow capturing, launching, cooling, selecting and detecting the Cesium atoms. [4]

The "Laser Source" is the subsystem providing all the laser beams needed for these optical interactions. It includes an optical bench and the dedicated electronics, to generate and control all the laser beams, with a high level of performances: spectral purity, high spectral and power stability, precise frequency tuning, high polarization ratio, etc.

Different kinds of passive and active optical components are required to obtain and control all the fine characteristics required for the laser beams: laser emitters, lenses, beamsplitters, acousto-optical modulators, shutters, optical fibers, etc.

The key components behavior and performances were characterized in the French laboratories of SYRTE (LPTF), CNES and ONERA, in the late 90's.

Optical architecture of the optical bench, choice and design of the components, were adapted in order to satisfy all the constraints of this space application: high level of performances but low volume, mass and electrical power allocations [5].

CNES chose EADS-SODERN, in June 2001, to precisely define and realize the Laser Source Engineering and Flight Models (idem for the Cesium Tube). Functional mock-ups of the key components were realized, characterized and pre-qualified between 2002 and 2003.

EADS-SODERN is now integrating the Laser Source Engineering Model (EM) and will deliver it to CNES to be tested in the PHARAO clock EM. EADS-SODERN is also integrating a Laser Source Structural and Thermal Model, and will submit it to flight mechanical and thermal conditions. The Laser Source Flight Model will then be integrated, qualified and delivered to CNES for integration in the PHARAO clock Flight Model.

2 PHARAO :

2.1 The PHARAO Project

The PHARAO project purpose is to demonstrate the performances improvement of space atomic clocks obtained by taking advantage of the very low atomic temperatures resulting from laser cooling techniques and microgravity environment [1].

The clock performances expected are a frequency accuracy of 1.10-16 and a relative stability of 0,7.10-14.τ-1/2 to 10-13.τ-1/2 where τ is the measurement time (about 2.10-16 over 1 day). These performances will allow a fine metrology of time and precise measurements on physical effects and constants[1].

The PHARAO clock design is based on LPTF and ENS/LKB studies on an initial earth version of the PHARAO clock, tested onboard a “0g flight” in 1997, which is one of the best earth laser cooled atomic clocks [2], [3].

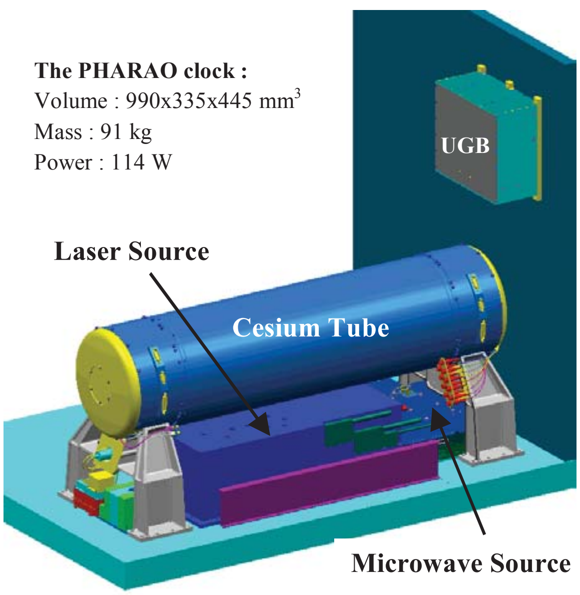

Fig. 1. 3D view of the PHARAO instrument

2.2 Atomic clock principle

The principle of a Cesium atomic clock is to lock a Microwave Source, including an ultra stable oscillator, on an hyperfine cesium transition near 9.192... GHz, which defines the international unit of time. This frequency control operates in a sequential mode:

First, about 10^8 atoms are captured and cooled in optical molasses at the intersection of six laser beams. Using the same set of laser beams, they are launched through the Cesium Tube with an adjustable velocity v and cooled down to 1 microKelvin, which corresponds to a rms velocity of about 7mm/s.

Unwanted quantum state atoms are pushed sideways by radiation pressure so that only F=3, m=0 atoms proceed further in the Cesium Tube in free flight. They interact twice with the microwave magnetic field in the interaction zone of the Ramsey cavity.

After these interactions, they enter the detection region, where the transition probability from the lower quantum state (F=3) to the upper one (F=4) is measured by light induced fluorescence using 2 laser beams. In the first beam, only atoms in the internal state F=4 are detected, and in the second beam only atoms in state F=3. The fluorescence is collected by 2 photodiodes and the resulting signal is processed by the control system. This completes one cycle of operation.

The transition probability measured is then used to lock the Microwave Source on the 9.192... GHz transition. This assures the stability over long periods of time.

Because the longer the microwave interactions, the better the frequency measurement accuracy, the atomic clock takes advantage to microgravity environment. Indeed, atoms can be launched with a very low speed without being deviated or stopped by the gravity which is the Earth atomic clocks lower limit. In microgravity, the interaction time can be made 5 to 10 times longer than in an Earth atomic clock.

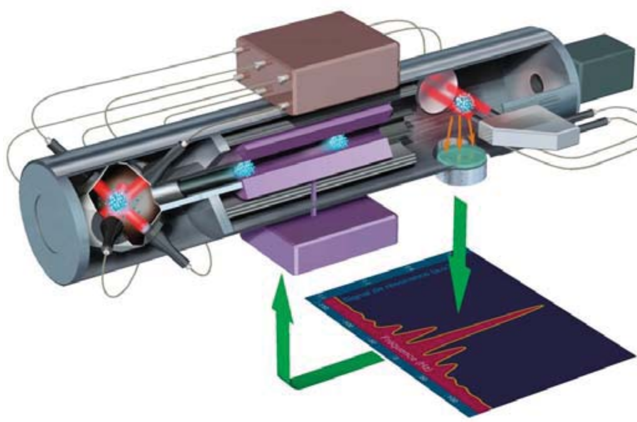

Fig. 2. Atomic clock principle in microgravity

2.3 Role of the laser beams

Laser signals are necessary to obtain the low atomic speed and long microwave interactions in the PHARAO clock. Indeed, obtaining low atomic speed implies to capture and cool the atoms. Then laser beams can be used to launch the atoms with a chosen low speed to optimize the microwave interaction time.

Laser beams also allows a selection of the atoms in the right energy level (F=3, m=0) to interact with the microwave signal, and eliminate the others (F=3, m≠0), before the microwave interaction. They can also be used to measure with a high S/N the number of atoms in the 3rd and the 4th energy level after the microwave interaction.

The optical interactions in the Cesium Tube require 14 laser signals :

- 6 laser beams which frequency is close to the “F=4-F’=5” transition of Cesium, for capture, cooling and launching
- 4 laser beams which frequency match the “F=3-F’=4” transition of Cesium, for repumping atoms in the right level to be captured ; these 4 laser beams are mixed with 4 of the 6 previous ones
- 2 laser beams for selection : one close to the “F=4-F’=5” transition and the other matching the “3-4” transition
- 2 laser beams for detection : one close to the “F=4-F’=5” transition and the other matching the “F=3-F’=4” transition

The Laser Source is the subsystem generating and controlling all the laser signals required. 10 optical fibers guide these laser signals from the optical bench of the Laser Source to the optical interaction parts of the Cesium Tube. Inside the Cesium Tube, optical components expand and orient the laser beams to optimize light-atoms interactions [4].

3 LASER SOURCE :

3.1 Main Requirements

The 6 “4-5 Capture laser beams” generated by the Laser Source must :

- have a single adjustable (by 1 MHz steps) frequency, 10 to 20 MHz lower than the one of the Cesium “4-5” absorption line, with an accuracy of +/- 1 MHz,
- have a power adjustable by 0.1 mW steps to more than 15 mW each,
- present a good long term power stability (variations lower than +/-1% over 20 days)
- and form 2 groups of synchronized and identical laser beams with orthogonal polarizations between the two groups and with relative differences in power lower than 2%.

The 4 “3-4 repumping laser beams” must have :

- a single frequency matching the “3-4” Cesium absorption line (with an accuracy of +/- 1 MHz),
- an adjustable power by 200 µW steps to a least 3 mW each,
- a good long term power stability (variations lower than +/-1% over 20 days),
- and be superposed to 4 of the 6 “4-5 capture laser beams”.

LAUNCHING the Cesium atoms at speed ranging from 0,05 m/s to 5m/s requires very fine variable frequency shifts of 3 among the 6 “4-5 capture laser beams”. The value of the frequency shift must be adjustable from 68 kHz to 6,8 MHz, by 68 kHz steps with a 1 kHz accuracy. The real value of the frequency shift must be known with a 10^{-4} accuracy compared to the expected value, and be stable over 20 days (variations lower than 10^{-4}).

LASER COOLING requires a very fine frequency and power control of the 6 “4-5 capture laser beams” over wide ranges :

- A monotone and linear decrease of the frequency during 300 to 500 µs, over a 75 MHz range, is required, with 5 MHz steps and +/-1 MHz accuracy

- A linear reduction of the power has to be obtained during the same time (same duration and delay lower than 10 µs), to a level included in the range 10^{-2} to 1 compared to the initial value).
- Then, an exponential decrease of the laser power is required to 1 percent of the previous value, with a duration adjustable between 100 and 300 µs.

SELECTING the f=3, m=0 Cesium atoms requires :

- 1 laser beam with a single adjustable frequency around the 4-5 one (from –5 to +5 MHz with a 0.2 MHz accuracy), a power adjustable by 1µW steps to at least 1,55 mW, with variations over 20 days lower than +/-1%
- and 1 laser beam matching the 3-4 frequency, a power adjustable by 0,1µW steps to at least 50 µW, with variations over 20 days lower than +/-1%

DETECTING the Cesium ratio of atoms in the F=4 and F=3 states after the microwave interaction requires

- 1 “4-5 laser beam” (divided into 2 in the Cesium Tube), with a power adjustable by 10 µW steps to at least 9,7 mW, with variations over 20 days lower than +/-1%, a single adjustable frequency around the 4-5 one (from –5 to +5 MHz with a 0.2 MHz accuracy), a high spectral purity (lower than 200 kHz), a low frequency noise (DSP <6,3 10^4 Hz²/Hz from 1 kHz to 1 GHz, DSP<10^7Hz²/Hz à 0,1 Hz) and a low Relative Intensity noise (RIN <$10^7$1/Hz à 0,1 Hz),
- and 1 laser beam matching the 3-4 frequency, with a power adjustable by 15 nW steps to at least 10 µW, with variations over 20 days lower than +/-1%.

A QUICK (<10 µs) AND TOTAL (-120DB) EXTINCTION of the laser beams is also required after optical interactions and before microwave interactions.

The laser beams must be LINEARLY POLARIZED to maximize the laser power delivered. The polarization is controlled on the optical bench, to generate the 14 laser signals from a minimum number of laser emitters, and finally insured by polarizing cubes and polarization maintaining optical fibers.

The high level of performances required implies the use of more than 150 optical components on the optical bench of the Laser Source. The very small volume allocated for the Laser Source force to use a very dense double-side 400 mm * 330 mm optical bench.

The auxiliary devices such as the laser current, voltage and temperature control units, the laser frequency-locking unit, the electronic drive for the acousto-optic modulators and the mechanisms, are located inside the Laser Source, on the plate below the optical bench.

The PHARAO Laser Source flight model has to withstand storage temperature in the -50°C to +75°C range (to be confirmed), a 35g quasi-static load and a random vibration at a level of 40g rms during launching. It is dedicated to operate in space for several years without any manual adjustment.

This implies a good stability of the laser beams characteristics between air and vacuum, after launching, and between integration and flight operating thermal conditions.

These constraints of performances, compactness and reliability, makes the PHARAO Laser Source a high technical challenge [4], [5]. High temperatures are difficult to sustain for some components like AOMs, and are negociated to guaranty a good flight operation.

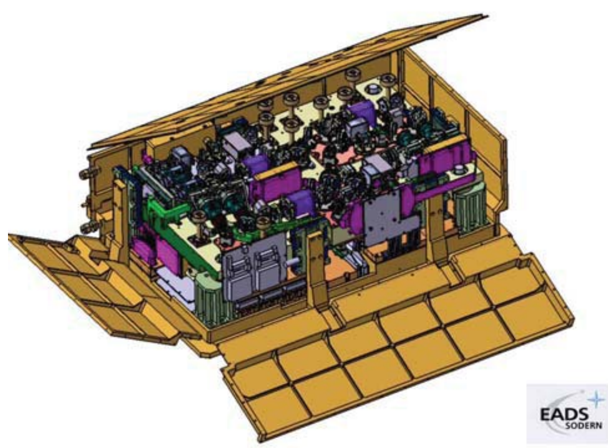

Fig. 3. 3D view of the Laser Source subsystem

3.2 Key components

The laser beams wavelength is around 852 nm.The specified optical power could be easily obtained with a compact free running laser diode. Unfortunately free running laser diodes are unsuitable for high precision spectroscopy purpose because of their large frequency line width (several MHz) and spectral mode hopping.

A stable single spectral line could be obtained with DFB (Distributed FeedBack) laser diode or DBR (Distributed Bragg Reflector) laser diode, but the frequency noise of available products is too high to achieve the required performances for PHARAO.

We chose an ECDL design (Extended Cavity Diode Laser) with a linear cavity and an intra cavity Fabry-Perot filter to select a single spectral line and obtain the spectral purity required. This laser design reduces the line-width of a free running laser diode by two orders of magnitude and enables to obtain the spectral purity required for the PHARAO clock. The feasibility and performances of this concept of ECDL for PHARAO were first demonstrated by BNM-SYRTE in 2000[5].

We use 2 ECDLs in the Laser Source to obtain the 2 optical reference frequencies of the Cesium (“4-5” and “3-4”) from which the various frequency shifts has to be precisely adjusted. They are frequency locked on Cesium saturated absorption lines using Cesium cells and dedicated electronic devices.

Extended Cavity Lasers (ECL) allow spectral widths 10 to 100 times lower than simple diodes, but supply a laser power about 3 to 5 times lower. This power is not sufficient to insure the different optical functions and semiconductor amplifiers are not reliable enough. So we have to use Slave Lasers locked in frequency by injecting in their cavity a part of the ECDL signal.

We use 2 Slave Lasers to obtain the laser power required for all the optical interactions with atoms using frequencies close to the “4-5” line.. A part of the laser signal emitted by the “4-5” ECDL is injected into the two Slave Lasers to be amplified without any variation of its spectrum.

Acousto-Optical Modulators are used to control the frequency and power of the laser beams to optimize each kind of optical interaction with Cesium atoms. They allow obtaining precise and variable frequency shifts from the atomic reference frequency on which the lasers are locked. The parameters used are the frequency and power of the RF signal injected into the AOM. 6 different AOMs are used to generate the various frequency shifts required.

We also use a lot of more traditional optical components such as mirrors, lenses, isolators, beam splitters, aspherical, and cylindrical lenses to adapt geometrical characteristics, generate the different laser beams, avoid optical feedback and minimize the losses in laser power.

7 mechanical shutters are used to obtain a total and synchronized extinction of the laser beams while switching the Acousto-Optical Modulators OFF allows obtaining the rapid extinction.

We use retardation plates and polarizing cubes to control the laser beams polarization and divide them toward the 10 Polarization-Maintaining optical fibers used to distribute them to the Cesium Tube.

3.3 Status of development

The Laser Source Engineering Model is being integrated at EADS-SODERN. The laser source is composed of 16 subsystems corresponding to different optical functions (beam mixing, frequency shifting, optical fiber injection…).

Each subsystem has already been pre-mounted (figure 4) and tested. The most critical components have been subjected to a pre-qualification campaign in order to control that they can sustain the mechanical and thermal environments during the launching and the space mission.

The integration of the 16 optical subsystems on the double-side optical bench is in process now. The optical output power in an optical fiber has preliminary shown the compliance of the laser power with the requirements.

The design of the Engineering Model will be comforted by a Laser Source Structural and Thermal Model (LSTM) which is being integrated and will then be tested under thermal and mechanical conditions representative of a flight. The (LSTM) will also enable to complete the set of data on the behavior of the critical components before the qualification of the Flight Model.

Fig. 4. Integration of a Laser Source subsystem.

4 EXTENDED CAVITY LASER DIODES

The optical bench requires a laser frequency stabilized close to the cesium D2 line (~350 THz), with an optical power of 30mW, a linewidth around a hundred of kHz, and a frequency noise spectral density lower than 10^4Hz2/Hz in the 100Hz to 1kHz range. A fast and accurate tuning of the laser frequency over 80MHz is also required.

An Extended Cavity Laser Diode is required to obtain this level of performances. EADS SODERN is developing the equipment, and characterizing its performances and environment behavior [6].

4.1 ECDL Optical design

Fig. 5 presents the scheme of the ECDL. The ECDL design has been developed with a 5420-C laser diode from JDS without any specific antireflection coating applied on the output facet. The free running diode emits up to 150mW optical power at a wavelength close to 852nm.

The temperature of the diode is stabilized with an electronic servo-loop to within a few mK and can be tuned from 17°C to 24°C. The emission wavelength of the diode at a temperature of 21°C is chosen approximately (within 3nm) to the desired wavelength. The laser diode is collimated with an aspherical lens.

The elliptic shape of the beam is anamorphosed with two cylindrical lenses in a near TEM00 gaussian mode with a 450µm beam waist.

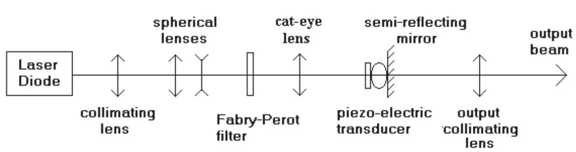

Fig. 5. ECDL Optical configuration.

The external cavity is closed with a semi-reflecting mirror, mounted in a cat's eye design so as to reduce the alignment sensitivity of the mirror. The optical path of the external cavity is 6.5cm long and it corresponds to an axial mode spacing of 2.3GHz.

The axial position of the semi-reflecting mirror of the external cavity can be tuned with a piezo-electric transducer (PZT). The cavity length changes by 2.1µm when a voltage of 40V is applied to the PZT.

Assuming that a variation ΔL of the optical path L of the external cavity yields a relative frequency detuning of an optical mode given by $\Delta\nu/\nu = -\Delta L/L$, the PZT enables to tune the laser frequency with a -280MHz/V slope.

The axial mode selection of the cavity is obtained with a thin intra-cavity silica Fabry-Perot filter. The frequency of the ECDL is selected by tilting the Fabry-Perot from the laser beam direction over a 13°C range.

The temperature sensitivity of the maximum transmission of the Fabry-Perot filter is -3.5 GHz/K. It is mainly induced by the silica refractive index change with temperature.

4.2 Thermo-Mechanical design

The ECDL mock-up is dedicated to operate on a +/-0.5K temperature stabilized aluminum bench, both in a laboratory atmosphere and in space-vacuum without any manual adjustment for several years.

In addition, the flight-model will have to stand a storage temperature in the -50°C to +75°C range, a 35g quasi-static load and a random vibration at a level of 40g rms.

We describe below the mechanical architecture of the mock-up, which is a preliminary design of the flight model.

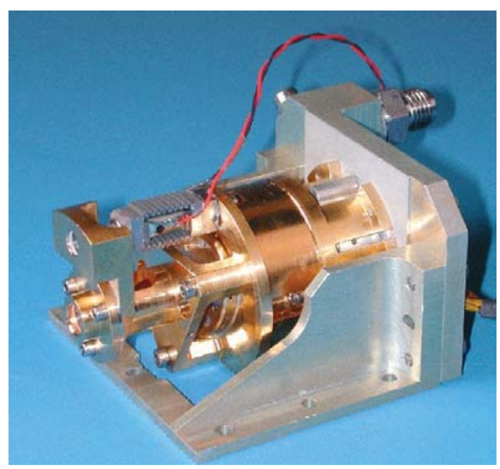

Fig. 6: ECDL Mock-Up

The mechanical design of the ECDL is composed of 4 parts: a collimated diode assembly, an anamorphic beam shaping ensemble, a Fabry-Perot mount assembly and a cat's eye with a PZT mounted mirror and a collimating output lens.

The laser diode and a heat sensor are cemented to a Peltier element. This ensemble is cemented to a base plate acting as a heatsink and interfaced to the bench with aluminum square.

The collimated lens is cemented to a mount which thickness is adjusted thanks to an iterative laser beam measurement until the laser beam is well collimated.

The lens mount is then bolted to the base plate with a 6µm transverse precision so as to adjust the laser beam direction within 2mrad.

The anamorphic beam shaping ensemble, the Fabry Perot mount assembly and the cat eye ensemble are made of Invar, so that a cavity length expansion due to a 1K temperature change can be compensated with a 10V correction applied to the PZT.

The position of the plano-convex cylindrical lens of the anamorphic beam shaping ensemble and the position of the collimating output lens are adjusted to within a few 20µm in the same way as the first collimating lens.

The Fabry-Perot tilt can be adjusted with a 10^{-4} rad resolution. The semi-reflecting mirror position of the external cavity is adjusted close to the cat's eye lens focal point within 50µm, by an iterative laser threshold current measurement.

A correct tuning of the semi-reflecting mirror position is characterized by a decrease of the free running diode threshold current from 12.5mA to a level of about 8.5mA.

A high stiffness assembly was designed with a finite element model. This model has shown that there should be no sliding at the screwed assembly's interfaces when the ECDL is submitted to a storage temperature in the -50°C to +75°C range and a 35g quasi-static load. Mechanical stresses were lower than the different materials elastic limits.

Pre-qualification test realized on the ECDL Mock-up confirmed a good behavior. Small residual angular changes measured after mechanical tests but causing no degradation on the laser operation will be corrected on the flight models.

4.3 Performances of the frequency-stabilized ECDL

We have operated the ECDL with diode injection current from 40 to 80mA and a diode temperature between 17°C and 24°C. The frequency of the mock-up is adjusted close to the cesium D2 line (~350THz).

The available laser power is 28mW for a diode laser injection current of 75mA. The far field angular diameter of the beam measured at 50% of the maximum is 0.7mrad in both directions.

For a given tilt of the Fabry-Perot filter, we have observed that a tuning of the diode laser temperature, current and PZT voltage enables a frequency setting of the ECDL in an approximate 10 GHz range around the central frequency selected by the Fabry-Perot filter.

We have measured frequency tuning slopes of 60MHz/mA +/-15 MHz/mA for the injection current and 190MHz/V +/-10MHz/V for the PZT voltage. The mode hop free scanning ranges are 2.5mA, 60mK, and 8.2V for diode injection current, diode temperature and PZT voltage respectively.

The operation of the Pharao clock requires that the ECDL frequency can be tuned in a -5MHz to 75MHz around the F=4-F'=5 hyperfine transition of the Cesium D2 line with a 1MHz accuracy.

The laser frequency is stabilized by a servo loop onto a saturated absorption of the cesium D2 line. ECLs are frequency locked on a cesium saturated absorption line by a servo loop, by using a cesium cell, to obtain high frequency stability. Acting on a piezo-electric actuator, which controls the cavity length allows slow frequency corrections, whereas acting on the laser current allows fast corrections.

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The optical configuration is shown in Fig. 7. A part of the laser beam, deflected by a polarizing cube passes through an acousto-optic modulator (AOM), double passes through a cesium cell and is detected with a 1mm2 photodiode.

Fig. 7: Optical configuration of the frequency servo-loop

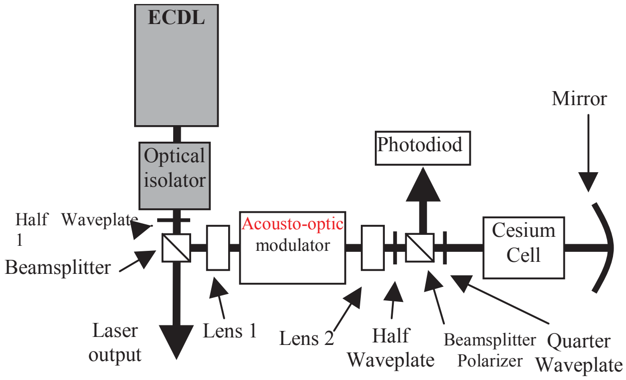
The laser frequency is modulated with a 500 kHz sine signal. The photodiode signal passes through a synchronous demodulator and a control circuit, to create the correction signal, which is then applied to the diode current and the PZT voltage. The laser frequency can be tuned using the acousto-optic modulator (AOM) which is placed inside the servo loop before the saturated absorption.

The laser output frequency is the frequency difference between the saturated absorption line frequency and the acousto-optic modulator frequency shift. The saturated absorption line is the F=4, F'=4/5 crossover of the cesium D2 line. The AOM frequency shift can be adjusted from -120 MHz to 200 MHz so that the output laser beam frequency can be tuned in a -5MHz to 75 MHz range around this reference frequency.

The AOM allows a fast and accurate laser frequency change in a 80MHz range, while keeping the servo-loop closed. We have measured a maximum slope of 200 GHz/s with a tracking error lower than 4 MHz.

The frequency noise spectral density of the laser can be evaluated in the 1Hz to 35 kHz range, with a measurement of the noise spectrum of the demodulated signal voltage of the saturated absorption photodiode.

We calibrate the frequency to voltage ratio of the demodulated signal of the photodiode, which is proportional (up to about 1 MHz) to the frequency difference between the laser radiation in a cesium cell and the saturated absorption line frequency.



We then measure the voltage noise spectrum density of the demodulated signal of the photodiode. The frequency noise induced by the AOM and the optical detection is significantly lower than the ECDL frequency noise. So the previous measurement gives a relevant estimation of the frequency noise spectral density of the 25mW ECDL output emission in the synchronous detection bandwidth.

The performances reached with the ECDL are a relative frequency accuracy of $3x10^{-9}$ and a frequency noise spectral density lower than $10^4 Hz^2/Hz$ in the range 100Hz to 1kHz. An acousto-optic modulator enables a fast and accurate tuning of the laser frequency, over a 80MHz range, with a rising time of 200GHz/s.

The Pharao clock must operate both in a laboratory atmosphere and in space vacuum. This requirement significantly impacts on the design and the setting of the laser cavity of the ECDL which contains high aperture diffraction limited lenses and a spectral filter with a high frequency accuracy requirement.

The design and the tuning process of the ECDL enable to have a satisfying quality factor of the laser cavity both in the air and in the vacuum. The intra cavity Fabry-Perot filter dedicated to axial laser mode selection has also been designed specifically for achieving an accurate frequency tuning on the cesium D2 line both in the atmosphere of a laboratory and in the vacuum.

We have already performed operating test of the ECDL during several weeks in a laboratory and in a vacuum chamber under a 10^{-8} atm pressure. Frequency noise spectrum and frequency accuracy are compliant with the requirements in both conditions.

The Engineering Models of the ECDL are already integrated.

Fig. 8: Engineering Model of the ECDL.

5 CONCLUSION

The PHARAO space atomic clock will be this first demonstration in space of clock performances improvement obtained with laser cooling techniques and microgravity.

Different laser beams, with very precise characteristics, are used before and after the microwave interaction in the clock. They allow an optimization of the atoms energy state and speed. This improves the quality of the microwave interaction and of the comparison between the Microwave Source frequency and the reference Cesium microwave transition à 9.192… GHz.

Therefore PHARAO requires a performant Laser Source able to generate, control and distribute all these laser beams. Designing the space PHARAO Laser Source, including an optical bench and all the related electronic devices, to provide all the laser beams required for the atomic manipulations, is a difficult task. The constraints of performance, compactness, low electrical consumption and space qualification are strong.

Developing the key components is also a challenge in matter of performance and space qualification. The Extended Cavity Laser Diodes is a good example of this challenge : this equipement has to be compact, very performant in air and in vacuum, and to sustain strong environmental constraints. Therefore we chose to use a linear cavity concept of ECDL with an intracavity Fabry-Perot filter.

The first results obtained by EADS-SODERN on this concept of ECDL have demonstrated that fast frequency tuning performances, frequency noise, and optical power of the ECDL, are compliant with PHARAO clock specifications. The results of the pre-qualification tests are also very encouraging. EADS-SODERN is now performing a long time operating test under vacuum. The results of those tests will enable to comfort the ECDL design for space applications.

According to these first results, the flight model under development is expected to be the most accurate and stable laser for space. Beyond the intended application of space-based cold atom clock, such a stabilized laser could also be a key element for future on-board instruments such as space interferometers or space LIDAR, for which a highly stable optical frequency standard is required.

The Laser Source Engineering Model integration is in progress, involving the ECDL and the different optical components and electronic devices required to generate and control all the laser beams required. The laser power delivered at the optical fiber output is compliant with the performances required to capture Cesium atoms. This Model will be delivered to CNES to be integrated and tested in the PHARAO clock EM.

EADS-SODERN will also integrate a Laser Source Structural and Thermal Model and submit it to mechanical and thermal flight conditions tests. This will complete the set of data on the behavior of the critical parts and components before qualification of the Flight Model. The Laser Source Flight Model will the be integrated, qualified and delivered to CNES for integration into the PHARAO clock Flight Model.

PHARAO will be the first demonstration of a compact and performant Laser Source for space clocks. Other laser cooled space atomic clocks are under study : in the USA, two projects of laser cooled space clocks similar to the PHARAO one are in progress (RACES and PARCS). In Europe (and mainly in France), some Cesium miniature clocks are under study for the Galileo project of european positioning system and for defense applications. Other kinds of instruments using laser cooled atoms are also under study (gyrometers for example).

Laser technologies are a key for future improvements in the area of time metrology and precise sensing for different kinds of applications (civile/defense positioning and communications, science,…). Improvements have still to be done to gain in compactness and reliability. Innovant technologies, like MOEMS and integrated optics, are under study to allow further miniaturization of this kind of laser devices (see the paper “New optical technology for cold atom experiment”, dedicated on this subject, at the same conference).

6 BIBLIOGRAPHY :

[1] C.Salomon and A.Clairon,"PHARAO: A cold atoms clock in space*", proposal in response to* ESA SP 1201 (1997).

[2] Ph. Laurent, P. Lemonde, E. Simon, G. Santarelli, A. Clairon, N. Dimarcq, P. Petit, C. Audouin, C. Salomon, “A cold atom clock in absence og gravity”, *Eur. Phys. J. D.*, vol.3, pp.201-204 (1998).

[3] M. Niering, R. Holzwarth, J. Reichert, P. Pokasov, T. Udem, M. Weitz, T. Hänsch, P. Lemonde, G. Santarelli, M. Abgrall, P. Laurent, C. Salomon, A. Clairon, *Phys. Rev. Lett*, 84, 5496 (2000)

[4]J. Loesel, J. Berthon, M. Saccoccio, N. Raimbault, Y. Aubry, A. Clairon, Ph. Laurent, P. Lemonde, “Optical design of PHARAO”, *ICSO* 2000.

[5]M. Saccoccio, J. Loesel, D. Blonde, J. Berthon,, P. Laurent, A. Clairon, M. Abgrall, S. Bize, Y. Sortais, Y. Aubry, “Study of optical design and key components for the PHARAO Laser Source”, in *Proc. of the symposium Optro 2002*, in Paris

[6] E. Simon, C. Coatantiec, M. Saccoccio, D. Blonde, J. Loesel, P. Laurent, I. Maksimovic, M. Abgrall, “ A highly stable frequency stabilised extended cavity diode laser for space”, *SPIE 2003* in St Etienne.