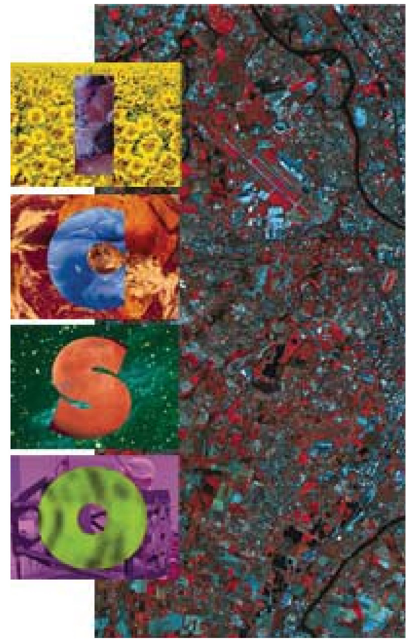
International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



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International Conference on Space Optics — ICSO 2000, edited by George Otrio, Proc. of SPIE Vol. 10569
105690T · © 2000 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307894

OPTICAL DESIGN OF PHARAO

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Abstract :
The purpose of the PHARAO project is to develop a new atomic clock generation in space. This clock takes advantage of the very low atomic velocities obtained by laser cooling techniques and the microgravity environment.
Designing the PHARAO optical bench, which provides all the laser tools for the atomic manipulations, is a difficult task. In this paper we will give a global overview of the optical bench in term of functions, interfaces and performances. After establishing the optical parameters, which have an impact on the atomic clock performance, we present the model and software, which are used for the design and analysis of the optical system, taking into account the Gaussian laser beams. Some critical functions have been experimented and characterized to prove the model's accuracy.

1 THE PHARAO PROJECT

PHARAO is a new generation of space clock using cold cesium atoms. It is a CNES project embarked on the ACES (Atomic Clock Ensemble in Space) payload which is an ESA (European Space Agency) project, and which will be launched to the ISS (International Space Station) near mid 2005. The purpose of the PHARAO project is to improve the performances of this type of atomic clocks by taking advantage of the very low temperatures obtained by laser cooling techniques and the microgravity environment. The clock performances are a frequency accuracy of 1.10^{-16} and a relative stability of $0,7.10^{-14}.\tau^{-1/2}$ to $10^{-13}.\tau^{-1/2}$ where τ is the measurement time (about 2.10^{-16} over 1 day). PHARAO will also allow some experiments on cold atom physics in conditions which are not accessible on Earth. These developments are the continuation of LPTF and ENS/LKB studies.

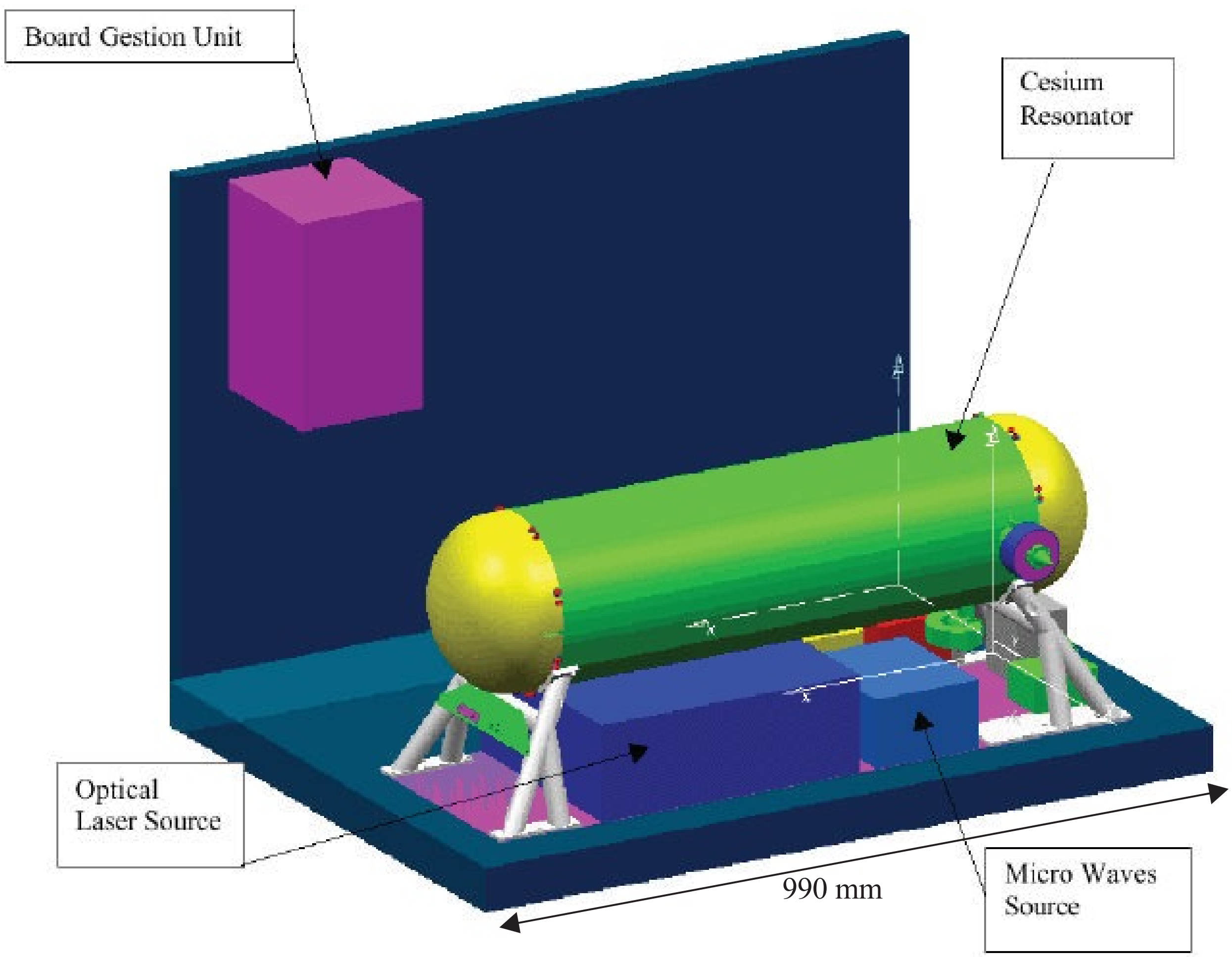

Figure 1 - 3D view of the PHARAO instrument

2 ATOMIC CLOCK PRINCIPLE

The principle of a cesium atomic clock is to lock the ultra stable oscillator on an hyperfine cesium transition near 9.19... 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 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 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 oscillator on the 9.19... GHz transition. This assures the oscillator 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 where the 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.

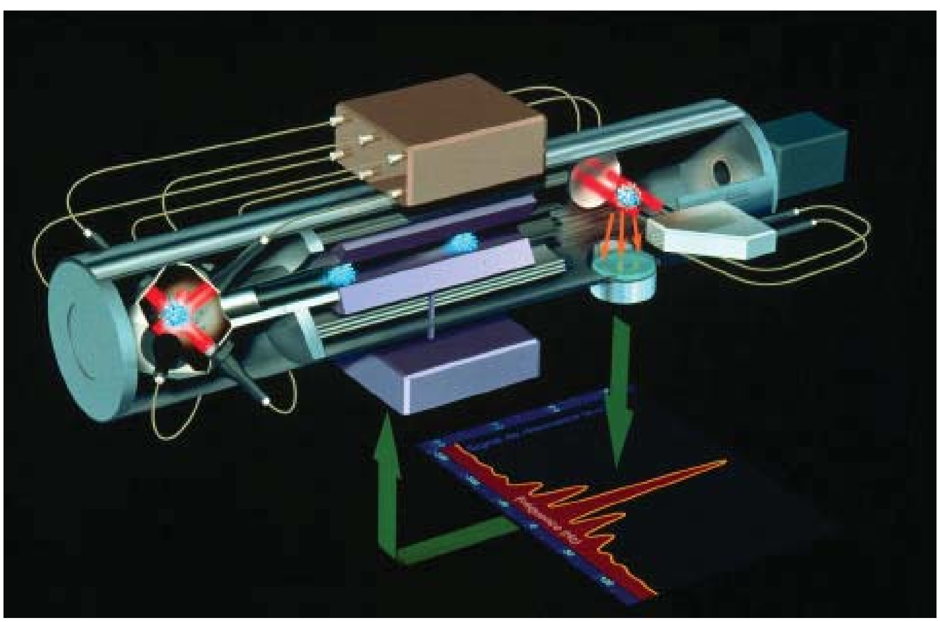

Figure 2– Atomic clock principle in microgravity

3 OPTICAL ARCHITECTURE AND MAIN REQUIREMENTS

The main PHARAO's optical functions are to capture and cool the atoms, to launch them with the adequate velocity, to select those which are in the right energy level and eliminate the others, and to measure with a high S/N the number of atoms in the 3^{rd} and the 4^{th} energy level after the microwave interaction. These functions are performed by 2 subsystems, the Laser Source where the laser beams are generated and the Cesium Resonator where the light-atoms interaction takes place. Optical fibers guide laser beams from the optical bench to the tube.

The Laser Source is designed to provide 2 different frequencies, distributed in 10 laser beams to the Cesium Resonator. 6 of these 10 laser beams which will be used for the capture function, need to have a relatively high power and to be accorded. The 10 beams must have a high spectral purity and stability, a precise frequency tuning from 34 KHz to 3.4 MHz and large frequency tuning over 80 MHz. Their power must be finely adjustable, controlled with a high stability and balanced at 1% between 2 laser beams. The beams need also to be precisely polarized with a high polarization ratio, and the Laser Source subsystem must be able to stop their transmission with a rapid and total extinction (120 dB). These strong requirements in addition to a very small volume allocated for the Laser Source force to use a very dense double-side 400 mm * 330 mm optical bench. The auxiliary equipments such as the laser current, voltage and temperature control units, the laser frequency – locking unit, and the electronic drive for the acousto-optic modulators and the mechanism are located inside the laser source, on the plate below the optical bench.

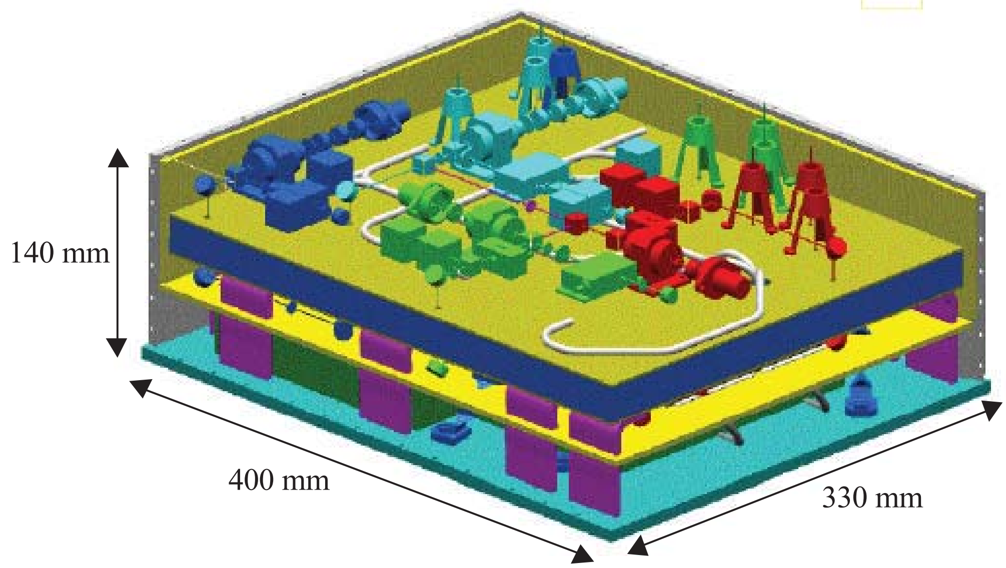

Figure 3 - 3D view of the Laser Source subsystem

The Cesium Resonator is the subsystem where the light-atoms interaction takes place. The laser beams are enlarged and collimated by specific optics that are in charge of fulfilling the geometric requirements such as size and alignment of the beams, and the radiometric requirements such as the radiant power, the irradiance, the state of polarization and the stray light rate. Relative diffusion below 10^{-6} is required for some optics. A part of the fluorescence resulting of the light-atom interaction must also be collected and concentrated on photodiodes by an optical collection system. This optical system must have a high collection efficiency whereas the fluorescence is a large and deep volumic source. Moreover this source emits a very low power of which only a little part, about 5%, will be collected by the photodiodes so that they must be able to measure a power flux of about 10^{-12} W with a high S/N.

4 MAIN COMPONENTS AND DEVICES

In order to achieve the optical requirements in the Laser Source and the cesium Resonator, more than 150 optical components are needed among which we can quote some rather specific components like 2 Extended Cavity Lasers and 2 Slave lasers, 6 acousto-optic modulators, 7 mechanical shutters, 10 polarizing fibers and 4 cesium cells. We also use lots of more traditional optical components such as mirrors, lenses, retardation plates, polarizing cube, isolators, beam splitters, aspherical, and cylindrical lenses.

4.1 Laser Source components

Extended Cavity Lasers (ECL) allow spectral purities 10 to 100 times better than simple diodes, but supply a laser power about 3 to 5 times lower. Because this power is not sufficient to insure the different optical functions and because semiconductors are not reliable enough we have to use Slave Lasers locked in frequency by injecting in their cavity a part of the Master Laser signal. ECLs are frequency locked on a cesium saturated absorption line by a servo loop, by using a cesium cell, to obtain high frequency stabilities. Slow frequency corrections are done by acting on a piezzo-electric actuator which controls the cavity length, whereas fast corrections are done by acting on the laser current. The optical frequencies of laser beams are then be shifted using acousto-optic modulators in order to optimize the interaction with the cesium atoms in the different parts of the Cesium Resonator. Then, a set of optical components controls the polarization and the power distribution toward the optical fibers.

4.2 Cesium Resonator components

One of the main difficulty here is to keep a very low stray light level whereas the Cesium resonator is crossed by 10 laser beams. We want to make the light interact with the atoms in only some precise parts of the resonator and absolutely avoid this interaction elsewhere. This constraint imposes to use very efficient multi-layer optical treatments: Anti-reflection coatings efficient even at high incidence angles, specular black metal-dielectric treatments, and reflecting coatings. Moreover several of these treatments must be deposed on the same optical window which complicates the deposition. Another stray light type is the hot atoms fluorescence, especially in the detection zone. Here, we take advantage of the Doppler effect to decrease the impact of hot atoms fluorescence: Leaning the laser beams of about 10° compared to the atoms propagation direction shift only the laser frequency seen by hot atoms, which speed is far greater than those of cold atoms. The result is that hot atoms are less excited and so they fluoresce less than cold atoms.

The high degree of compactness is another constraint and has an impact on the components used for both the 10 collimators and the collection system. The collimators must have 2 lenses: A divergent one to increase the divergence of the beam and a convergent one to collimate it. Moreover, some beams need to have rectangular sections. That imposes a cylindrical lens in addition to the other lenses. The collimators must also have beam splitters and retardation plates to balance the power flux and control the polarization state. About the collection system, aspherical lenses with strong curvatures and good anti-reflection coatings are needed. Collection system using elliptic mirror condenser is also considered.

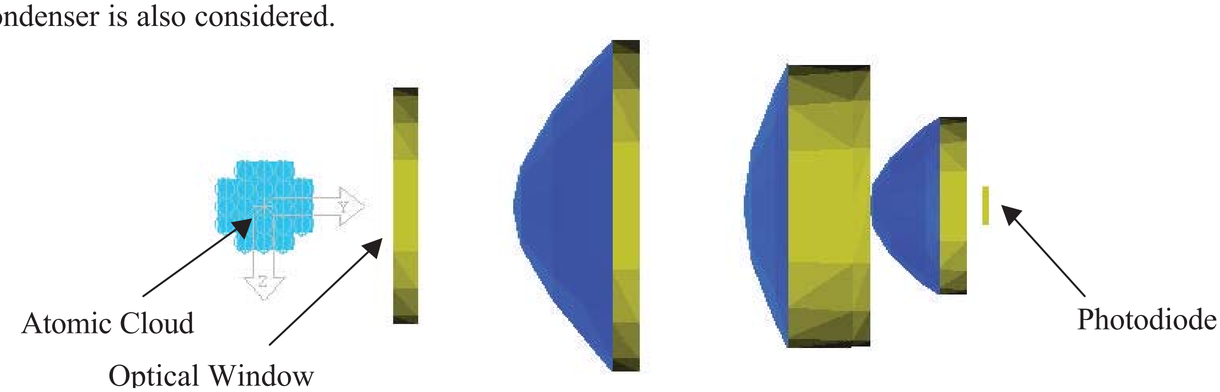

Figure 4 - The collection system considered

5 LASER SOURCE SIMULATIONS

As we need to find a high level of compactness design while minimizing the potential degradation of performances, some critical components has to be qualified for space use with less overall dimensions and consumption. This leads to model, experiment and characterize a precise design to prove its feasibility. In this part of the article, we will focus on 1 laser string of the Laser Source. Its modelization and comparison with experimental results will be developed: first we will deal with Gaussian beams modeling and Code V optical code possibilities. A description of the laser string will be given, and we will end up with the comparison between modelizations and experimental results.

Gaussian Beams require special consideration as they have specific transformation properties. These properties need to be understood to be able to optimize the optics for a particular laser string. To specify and discuss propagation characteristics of laser beam provided by the Laser Source we have to define its waist diameter.

The laser beam radius of the Laser Source are typically between 150 and 350 µm. So, their divergence are between 0.78 mrad to 1.81mrad, then, not negligible Compared to optical propagation lengths. The common laws of geometrical optics do not adequately predict the positions and sizes of the beam at the focus. It is necessary to take into account the diffraction theory which predicts with precision the spreading of the laser beam.

The optical computer code "Code V" has several functions dealing with gaussian beams propagation among which BEA (BEAm propagation) and PSF (Point Spread Function) have been used in our models.

The BEA function is a first order beam propagation approximation. It is useful to determine the waist locations and sizes along chief rays and to analyze the propagation of optical beams through the systems but it does not include other aberration effects than local astigmatism. The mathematical method used is based on a generalized 4*4 complex ABCD matrix defined from beam spreading and curvature. Beam spreading and curvature are linked to the z distance from the flat wavefront plane, the wavelength , and the waist radius.

The PSF function is used when diffraction effects are significant. It allows to examine beam intensity and phase at any surface in the optical system, including diffraction effects. This options is useful to design laser systems having large f-number such as our laser diodes. Coupling efficiency of a diffraction image into a single mode fiber can also be computed. The input Gaussian beam parameters are defined with the radius of the beam at $1/e^2$, the initial wavefront radius of curvature, or the entrance pupil apodization which seems to be more useful for fast computations. Gaussian apodization option uses the Gaussian intensity distribution apodized across the entrance pupil ($1/e^2$) and the ratio of the beam radius on the entrance pupil and the entrance pupil radius, for both orthogonal axes.

Acousto-Optic Modulators can not be modeled with diffraction based propagation. Actually there is no software able to simulate the bulk diffraction that takes place in an acousto-optic material. The only way to integrate such components in our model is to simulate the diffraction of the equivalent grating. But they are treated with geometrical ray tracing methods, and the polarization state is not taken into account.

5.1 Optical model of the Capture laser string

The laser diode characteristics are Wox = 0.6µm and Woy 2.1µm, a central wavelength of 852 nm, and an astigmatism between 0 and 5µm. The collimating optic (Lo) is made of a 2.75mm focal lens. Its large aperture being f / 0.874, the adjustment of the diode with respect to the collimator is very sensitive. The resulting collimated beam is astigmatic with a ratio of 3 between its 2 axes.

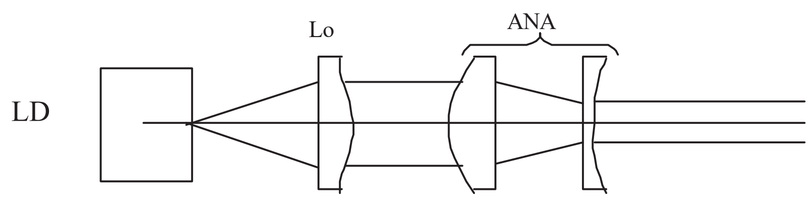

Figure 5 - Source Laser Diode and its anamorphoser

The anamorphoser (ANA) consists of two cylindrical lenses. Its advantage is the lower sensibility to the angular deviation between the vacuum and the ambient pressure. It changes the collimated elliptical beam to a collimated circular beam with a diameter of 0.7mm. ¼ and ½ wave retardation plates, and polarizing beamsplitter cubes control the distribution ratio of the power by mean of the polarization state control (cf. figure 7). An optical isolator protects the laser source from optical feedback which would induce perturbations on the laser frequency. An acousto-optic modulator (AOM) adapts the beam frequency for the Capture function. This component is modeled by a crystal with a grating in the middle which simulates the deflection of the diffractive order of +1. For the reference wavelength, the deviation is about 14° with respect to the 0^{th} order. Cutted angles of crystals are also taken into account. Efficiency coefficient of AOM is optimized for the situation where the wavefront is flat in the middle of the component and for a waist radius of 150 µm. Two afocals, composed of two spherical lenses, adapt the diameters of the collimated beam to the expected radius inside the AOM to 150 µm and before fiber injection to 300 µm.

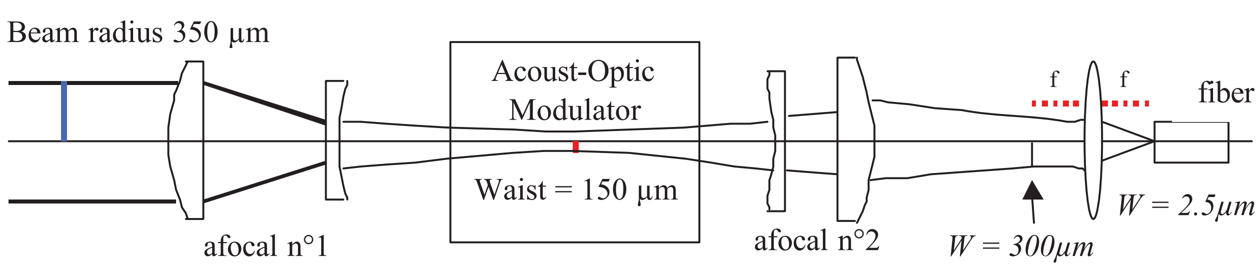

Figure 6 - The acousto-optic modulator and its optics

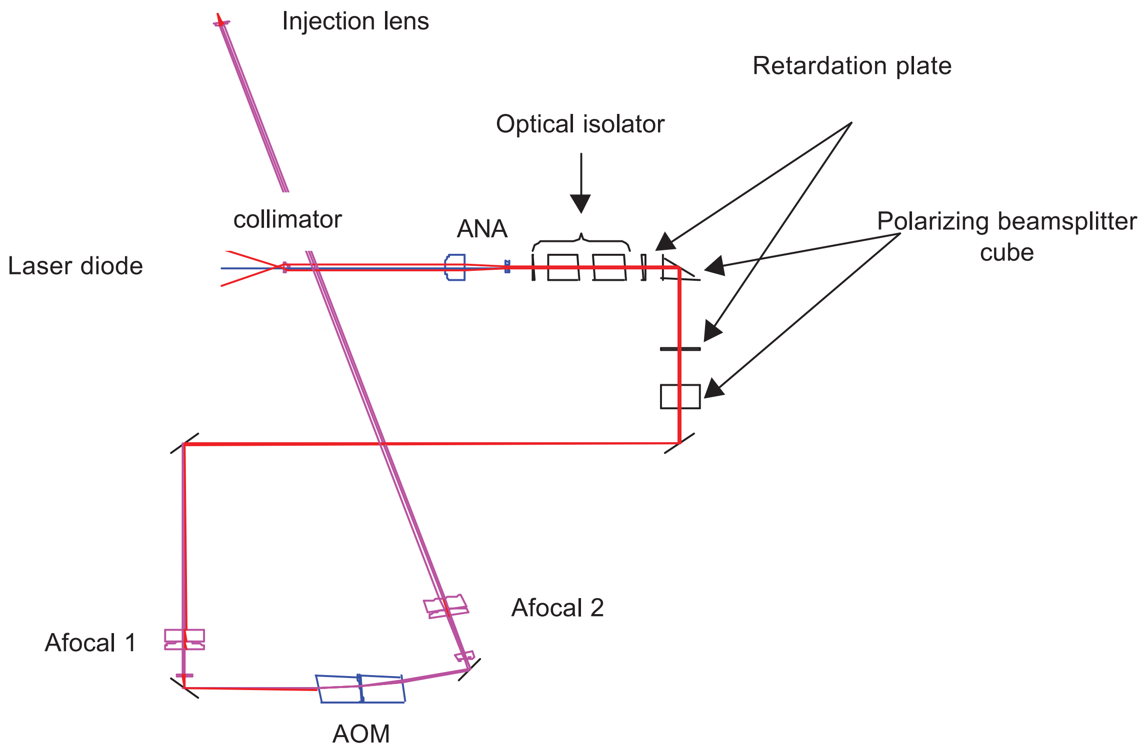

Figure 7 - Global view of the capture beam generation system

5.2 Experimental validation

We have experimented one of the Capture way on an optical bench, analyzed its performances and compared them with those given by the optical model above. The results are presented in the table below:

			code V computations				measurements	
Requirements (theoretical values)			*First order (BEA)*		*diffraction (PSF)*		(with 10% error)	
	X axis	Y axis	X axis	Y axis	X axis	Y axis	X axis	Y axis
	µm	µm	µm	µm	µm	µm	µm	µm
Beam radius output collimator	1300	350	1240	355	1200	355	1200	322
Beam radius output ANA	350	350	350	350	350	360	350	350
Beam radius inside AOM	150	150	143	144	120	148	124	id
Beam radius before injection	500	500	472	475	440	464	495	id
Beam radius in the image plane	2.5	2.5	2.8	2.8	2.9	2.6	3.16	id
Couple efficiency *	>80%		/		98.76%		93%	

* The efficiency coefficient is the percentage of energy coupled in the optical fiber. This parameter can not be computed with the BEA function which doesn't take into account diffraction effects.

	code V computations		**measurements**
	First order (BEA)	***diffraction (PSF)***	(with 10% error)
Distance between :	mm	mm	mm
Laser diode and collim.	1.5612	1.5630	Not measured
Two lenses of ANA	11.6594	11.66	11.15
Two lenses of AFO_1	12.51	11.40	12.62
Two lenses of AFO_2	17.72	16.79	17.98
Image distance	4.284	4.29	4.22

Models using first order computation (BEA) and those using diffraction computation (PSF) give both similar results, in very good accordance with measurements, but with just some small differences which could be explained by several parameters: Some experimental focal lengths used can be different of more than 2% compared to theoretical values, and the laser diode internal astigmatism isn't taken into account in the models. The calculations will be carried on to test alignment sensitivities.

6 CONCLUSION

PHARAO is a new generation atomic clock using cold atoms with exceptional accuracy and stability. The optical design is close to be finished and most of its optical combinations have been simulated and experimentally tested. It can be concluded that the optical bench with external cavity semiconductor lasers and a high level of compactness allow to achieve the expected accuracies. PHARAO does not require any significant developments but is nevertheless a highly innovative project from technical and scientific viewpoints.

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