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## HIGH RESOLUTION ATOM INTERFEROMETRY WITH OPTICAL RESONATORS

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### I. INTRODUCTION

During the past decades, atom interferometry experiments were developed for various applications like precision measurement of fundamental constants [1, 2], gravimetry [3], gradiometry [4] or inertial sensing [5, 6]. Based on these methods, cold atoms sensors measure interferometrically the inertial effects affecting the experiment with respect to free falling laser-cooled atoms that are split and recombined using two counter-propagating laser beams.

The scale factor of those inertial sensors is proportional with the number  $2n$  of photons transferred from the interrogation laser beams to the atoms and can be significantly improved by using large momentum transfer (LMT) techniques [7, 8]. However, those techniques require high-power laser beams [9] that are currently limiting the maximum achievable LMT order. A solution to improve the available laser power is to perform atom interferometry with cavity enhanced pulses [10]. On the other hand, interrogating the atoms in optical resonators could be used to relax the power requirements in the state of the art atom sensors, so as to simplify the interrogation laser systems. Cavity interrogation is therefore a strong asset for the realization of embedded atom interferometer experiments, as well as commercial matter-wave sensors and future space instruments.

Cavity atom interferometry is at the heart of the MIGA (Matter-wave laser Interferometer Gravitation Antenna) project [11]. MIGA aims at developing a demonstrator for gravitational wave detection to study the strain tensor of space-time and gravitation in the infrasound frequency band 100 mHz-1 Hz. MIGA will allow to broaden the observable gravitational waves frequency range of ground-based optical detectors like LIGO, which are limited under few tens of Herzs by several sources of cavity length noise that mimic the effect of gravitational waves. MIGA will consist in an array of atomic interferometers simultaneously manipulated by the resonant optical field of a 350 m horizontal cavity. This large scale experiment will bring to novel applications in both geophysics and fundamental physics.

In this frame, we are currently developing at the LP2N (Laboratoire de Photonique Numérique et Nanosciences) laboratory a cold atom accelerometer in a fountain configuration with cavity-enhanced interrogation pulses to demonstrate Bragg interrogation in a cavity also in the LMT regime. A second experimental setup, which consists in a 5 m long baseline gradiometer prototype is currently in the design phase, and it will prove the technical feasibility of the project and help to test all the different equipments that will be used in the final experiment.

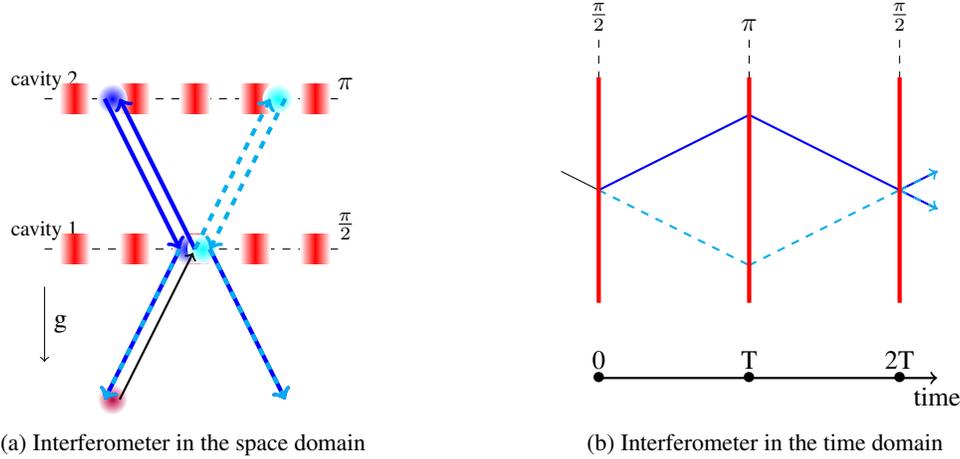
In this article, we will present the principle of the MIGA project and its architecture, and the two preliminary experiments developed at the LP2N laboratory.

### II. GRAVITATIONAL WAVES DETECTION WITH AN ARRAY OF ATOM INTERFEROMETERS

The MIGA antenna will consist of a set of 87Rb atom interferometers simultaneously interrogated by the resonant field of a 350 m long horizontal cavity. Each atom interferometer will benefit from cavity-enhanced large momentum transfer beam splitters and will simultaneously read out the motion of the cavity, gravitational waves and inertial effects. These contributions can be separated by correlating the signal of the three atomic sensors placed along the optical cavity: the motion of the cavity will be seen as common noise, gravitational waves effects as gravity gradients while inertial effects contribution will have a spatial signature [12].

### A. Acceleration measurement with one atom interferometer

The atoms are manipulated by a sequence of three Bragg pulses generated in the cavities. Bragg diffraction [13] couples the external atomic states  $|+\hbar k\rangle$  and  $|-\hbar k\rangle$  where  $k$  is the wave vector of the interrogation light field.



**Figure 1:** Scheme of the interferometers in the space and in the time domain. The dark blue and the dashed light blue lines represent the two arms of the matter-wave interferometer.

The interferometer sequence is presented in figure 1 both in the space and the time domain. The atoms are first in the  $|+\hbar k\rangle$  state. When they reach the first cavity, the matter wave is split by a first pulse  $\pi/2$  that put the atoms in an equiprobable superposition of the states  $|+\hbar k\rangle$  and  $|-\hbar k\rangle$ . When the atoms reach the apex of their trajectory, they are deflected by a pulse  $\pi$  which reverses the atomic states. When the atomic cloud crosses back the first cavity, a last pulse  $\pi/2$  closes the interferometer. The transition probability  $P$  between the two external states is:

$$P = \frac{1}{2}(1 - \cos\Delta\phi_{AT}) \quad (1)$$

where  $\Delta\phi_{AT}$  is the atom phase shift.

### B. Strain measurement with an array of atom interferometers

The atom phase shift  $\Delta\phi_{AT}$  at the output of an atom interferometer at the position  $X_i$  in an array of atom interferometer depends on the local horizontal acceleration of the experiment frame with respect to the atomic cloud reference frame  $a(X_i)$  and on the strain variation induced by gravitational waves  $h$ . We also need to take into account the main noise sources: the fluctuations of the output mirror position  $x_2$ , the laser frequency fluctuations  $\delta\nu$  and the detection noise  $\epsilon(X_i)$ . It is shown in [12] that the effect of the fluctuations of the input mirror position  $x_1$  can be neglected. The expression of  $\Delta\Phi_{AT}$  is:

$$\Delta\phi_{AT}(X_i) = \frac{4\pi\nu_0}{c}s_{x2} + \frac{4\pi}{c}[-s_{\delta\nu} + \frac{\nu_0}{2}s_h](X_i - L) + s_a(X_i) + \epsilon(X_i) \quad (2)$$

where  $\nu_0$  is the laser frequency,  $L$  is the mean length of the cavity and  $s_u$  is the convolution of the time-fluctuation of effect  $u(t)$  by the atom interferometer sensitivity function  $s(t)$  [14].

Combining the signals of two atom interferometers of the array allows to get rid of the effect of the output mirror position fluctuations:

$$\Delta\phi_{AT}(X_i) - \Delta\phi_{AT}(X_j) = \frac{4\pi}{c}[-s_{\delta\nu} + \frac{\nu_0}{2}s_h](X_i - X_j) + s_a(X_i) - s_a(X_j) + \epsilon(X_i) - \epsilon(X_j) \quad (3)$$

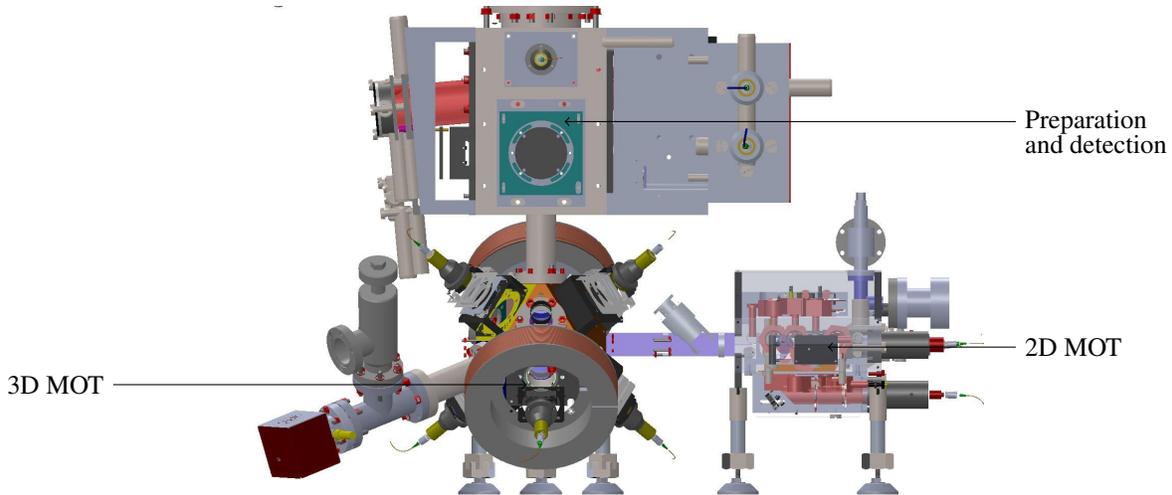
In this gradiometer configuration, the sensor becomes extremely robust to the cavity vibrations. However, the signal combines the effect of local gravity gradient with the gravitational waves signature. To be able to differentiate those two contributions, we should consider several couples of interferometers in the set with different baselines [12]. Beyond gravitational waves detection, the measurement of local gravity gradients can be very interesting for applications in geophysics as hydrology or underground survey.

### III. THE MIGA ANTENNA

We are currently developing the hybrid detector called MIGA, which will consist in 3 atom interferometers simultaneously interrogated by the resonant optical field of a 350 m long cavity. It will be a demonstrator for gravitational wave detection with cold atoms and will be implemented in the LSBB (Laboratoire Souterrain Bas Bruit) laboratory.

#### A. Cold atom sources

The cold atom sources are developed at the SYRTE (SYstèmes de Référence Temps Espace) laboratory. It performs the preparation of the atomic cloud and the detection of the state of the atoms after the interferometer. A scheme of the atom source is presented on figure 2. The  $^{87}\text{Rb}$  atoms are loaded in a 2D magneto-optical trap (MOT) which feeds the 3D MOT. The atomic cloud is launched almost vertically. After a phase of moving molasse, the temperature of the cloud is lower than  $5 \mu\text{K}$ . We then select the atoms so that they are in the magnetic state  $m_F = 0$  and they have the good transverse velocity class to fulfill the angle of Bragg requirement when they reach the optical cavities. Initially, the atoms are in the



**Figure 2:** Scheme of the cold atom sources used on the MIGA instrument.

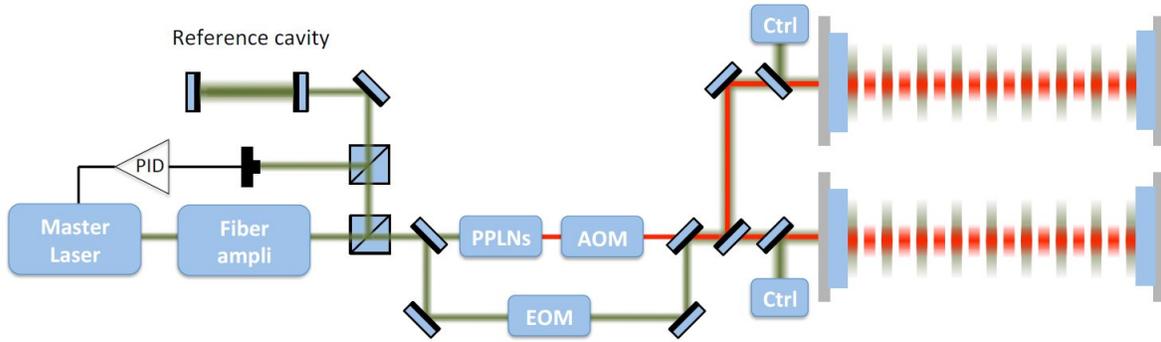
state  $|F = 2 \rangle$ . The magnetic state is selected by applying a first Raman pulse which will populate mainly the state  $|f = 1, m_F = 0 \rangle$ . The atoms remaining in the state  $|F = 2 \rangle$  are then blasted. We apply a second Raman pulse to transfer the atoms from the state  $|F = 1, m_F = 0 \rangle$  to the state  $|F = 2, m_F = 0 \rangle$ . This pulse is long so that it is velocity selective. The atoms remaining in the state  $|F = 1 \rangle$  are blasted by a second push beam.

After the interferometer, the atoms fall back through the detection system. A short Raman pulse is applied for the external state labeling: the atoms in the external state  $|F = 2, -\hbar k \rangle$  are transferred in the state  $|F = 1, +\hbar k \rangle$ . The detection is then done by fluorescence.

#### B. Laser and interrogation cavities

To generate the interferometer pulses, laser light at 780 nm resonant with the plan-concave cavities is needed. However, the pulses have to be short to avoid to be too selective in velocity. Therefore, it is not possible to lock the cavities on the laser at 780 nm. A laser beam at 1560 nm is used as an optical link to maintain the alignment of the cavities and a part of this beam is frequency doubled to generate 780 nm pulses. The optical apparatus is presented on figure 3.

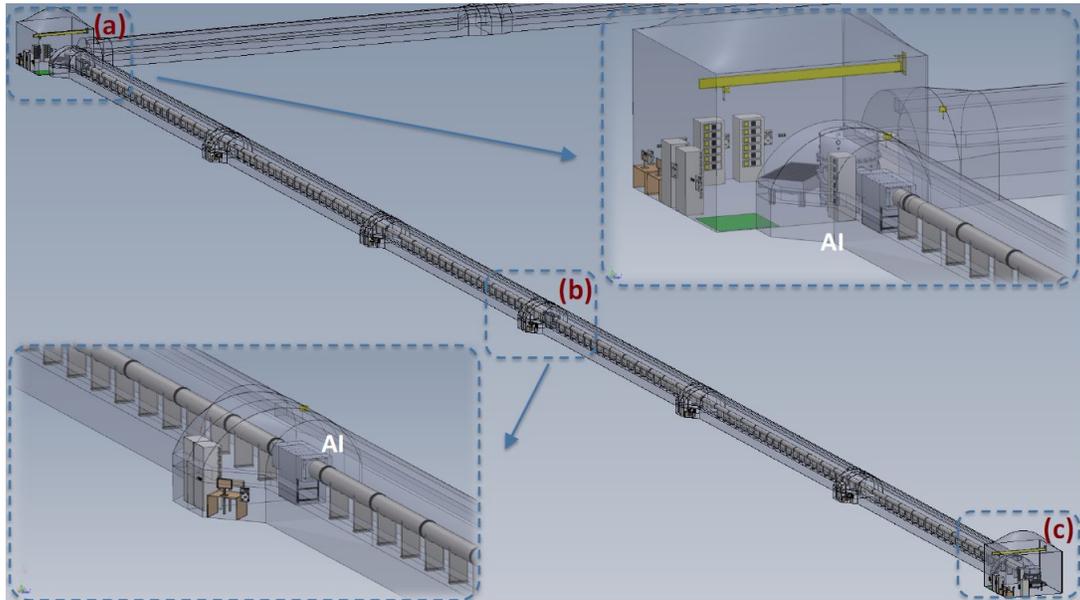
The master laser at 1560 nm is stabilized at the  $d\nu/\nu = 10^{-15} \text{ Hz}^{-1/2}$  level with a highly stable reference cavity. A small amount of the 1560 nm radiations is used to lock the cavities: the resonance of the cavity is kept using the Pound-Drever-Hall technique [15] and the angular alignment is conserved with the Ward method [16]. The side-bands needed by these two techniques are generated by an Electro-Optic Modulator (EOM) before the light enters the cavities. The other part of the 1560 nm radiations is doubled with a Periodically Pole Lithium Niobate (PPLN) crystal to obtain the 780 nm beam. The impulsions are then generated by Acousto-Optics Modulator (AOM).



**Figure 3:** Scheme of the cavities and of the laser system on the MIGA antenna. Adapted from [11].

### C. Sites infrastructure

The antenna will be implemented 500 m underground at the LSBB laboratory in Rustrel, France, where it will benefit from an ultra low noise facility. A scheme of the planned infrastructures is shown on figure 4.



**Figure 4:** Scheme of the infrastructure planned for the MIGA antenna at LSBB. B. The AIs of the initial antenna will be located at (a), (b) and (c). Optical setups for cavity injection will be hosted in room (a). Adapted from [11].

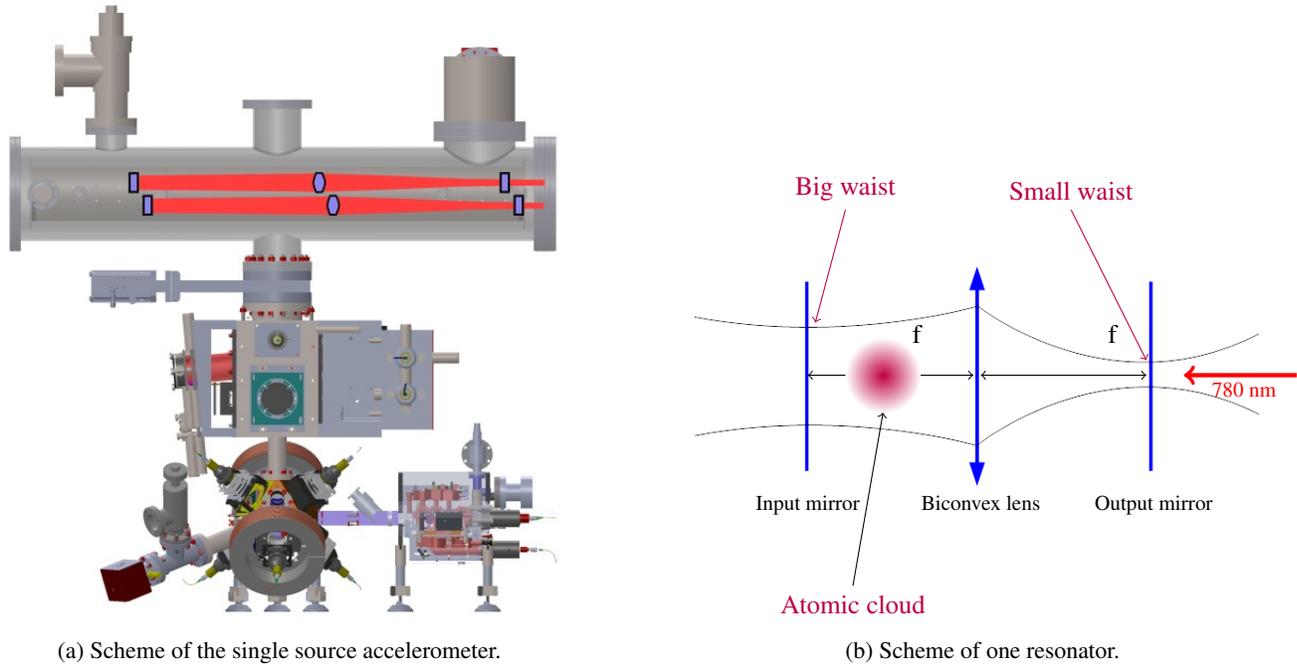
Two perpendicular 350 m long galleries, 3.2 m width, will host the instrument. The antenna will first consist of 3 atom sources equally spaced along one gallery, located in (a), (b) and (c) on figure 4. Future improvements are possible: a second 350 m long gallery can be used for a 2D antenna and both galleries will have empty widenings to keep the possibility of increasing the number of atom interferometers and the spatial resolution of the instrument.

## IV. THE COLD ATOM ACCELEROMETER AND THE 5 M LONG BASELINE PROTOTYPE

In parallel of the conception of the MIGA antenna, two prototypes are developed at the LP2N laboratory: a single source accelerometer and a high sensitivity gradiometer.

A. The single source accelerometer

The single source accelerometer (presented on figure 5a) will help to prove the feasibility of fountain interferometer with cavity-enhanced pulses. This experiment is currently under assembly. The pulses are generated in 80 cm long cavities. A



**Figure 5:** Scheme of the MIGA preliminary experiment (a) and of the cavities used to generate the atom interferometer (b).  $f$  is the focal length of the biconvex lens. The two cavity mirrors are flat.

plan-concave cavity of this dimension with a concave mirror with a radius of curvature 2 m will have a waist smaller than  $500 \mu\text{m}$  (considering light with a wavelength of 780 nm). At the top of the parabola, because of thermal expansion, the atomic cloud has a diameter about 1 cm. It is therefore not possible to use this kind of cavity in this short setup.

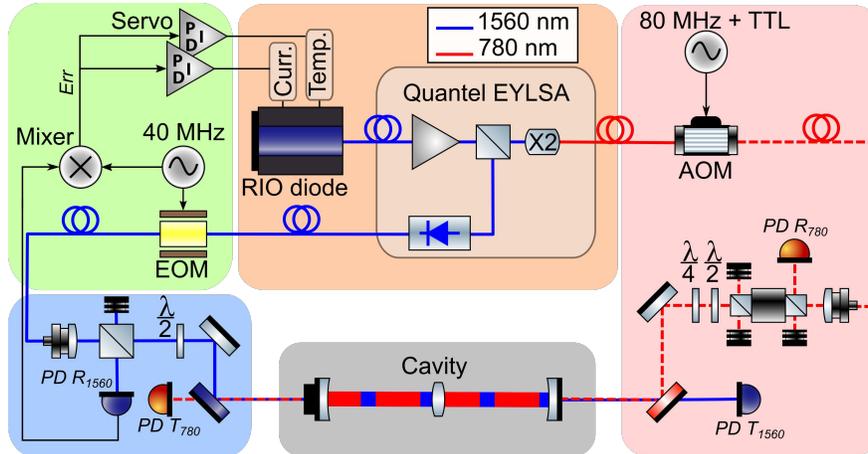
We developed a stable and compact setup of resonator with two mirrors and an intra-cavity optical system (see figure 5b) [17]. The flat mirrors are placed in the object and image focal planes of the intra-cavity optical system. Entering this resonator with a waist  $\omega_{01}$  on the input mirror will result in having a waist  $\omega_{02}$  on the output mirror with:

$$\omega_{02} = \frac{\lambda f}{\pi \omega_{01}} \quad (4)$$

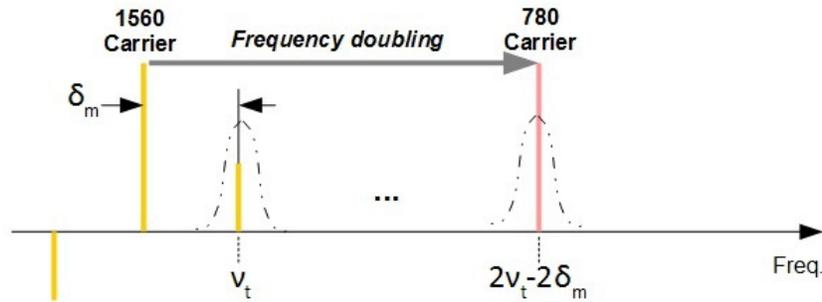
With the wavelength  $\lambda=780 \text{ nm}$ , the focal length  $f=40 \text{ cm}$  and the input waist  $\omega_{01}=10 \mu\text{m}$ , the waist  $\omega_{02}$  in the second half of the cavity is about 1 cm, which is sufficient to interrogate the atomic cloud.

The method used to keep the laser at 780 nm resonant with the cavity slightly differs from the one used on the final apparatus: unlike the MIGA antenna and its suspended cavities, on this preliminary experiment the 1560 nm optical link laser beam is directly referenced on the resonator, which is rigid. As seen on figure 6a, a fibered RIO diode at 1560 nm seeds the Quantel EYLSA amplifier which provides two outputs: one amplified 100 mW output at 1560 nm and one output at 780 nm where the power can be tuned from 100 mW to 1 W. The 1560 nm output is injected in the cavity and used to lock the RIO laser diode on the resonator and the 780 nm output is used to generate the interferometer cavity enhanced pulses.

The optics of the resonator have a double coating to provide high reflectivity for both wavelengths. Because the cavity doesn't have exactly the same length for the two wavelengths, the frequency of the 780 nm laser beam can't just be the double of the one of the 1560 nm optical link. To tune the frequency of the 780 nm laser with respect to the optical link frequency, we use the method presented on figure 6b: after the modulation, done by an EOM, instead of injecting the carrier in the cavity as in the classical Pound Drever Hall method, we use a side-band to lock the 1560 nm laser diode. However, it is the frequency of the carrier which is doubled to generate the 780 nm light. Therefore, it is possible to tune the frequency of the 780 nm laser beam so that it is resonant with the cavity by changing the modulation frequency applied on the EOM [18].



(a) Scheme of the optical bench used on the MIGA preliminary experiment



(b) Method used to tune the 780 nm light frequency with respect to the 1560 nm optical link.

**Figure 6:** Optical apparatus (a) and method used to generate the 780 nm light beam (b). On (b), the dashed Gaussians show the width of the cavity at 1560 nm and at 780 nm,  $\nu_t$  is the frequency of the side-band used to lock the 1560 nm laser diode on the cavity,  $\delta_m$  is the modulation frequency. The frequency of the 780 nm laser beam is  $2\nu_t - 2\delta_m$ .

### B. The high sensitivity gradiometer

To test the correlations between two atom interferometers interrogated in the same optical cavities, in particular the reduction of the mirror vibration noise, a high sensitivity gradiometer is under development.

A scheme of this experiment is presented on figure 7. Two atom interferometers will be simultaneously interrogated by the resonant field of 5 m long cavities. The mirrors of those plan concave resonators will be suspended and the laser system and the suspension system will be the same than for the final MIGA experiment. This prototype will help us to test all the equipment that will be used on the underground setup and will remain in the LP2N laboratory as a test bench for future upgrades of the MIGA antenna.

## V. CONCLUSION

The MIGA antenna will provide a high sensitivity measurement of gravity gradients and curvature, opening the way to sub-Hz ground based gravitational wave detectors based on cold atoms technologies. Moreover, it will contribute to the survey of the mass distribution around the instrument, which is of great interest for geophysics applications as hydrology.

The single source accelerometer will give a proof of principle for the cavity-enhanced LMT beam-splitters and for atom interferometry in cavities in a fountain configuration. The 5 m long baseline gradiometer will be a test bench for all the equipment used on the final MIGA antenna and for all the future improvements.

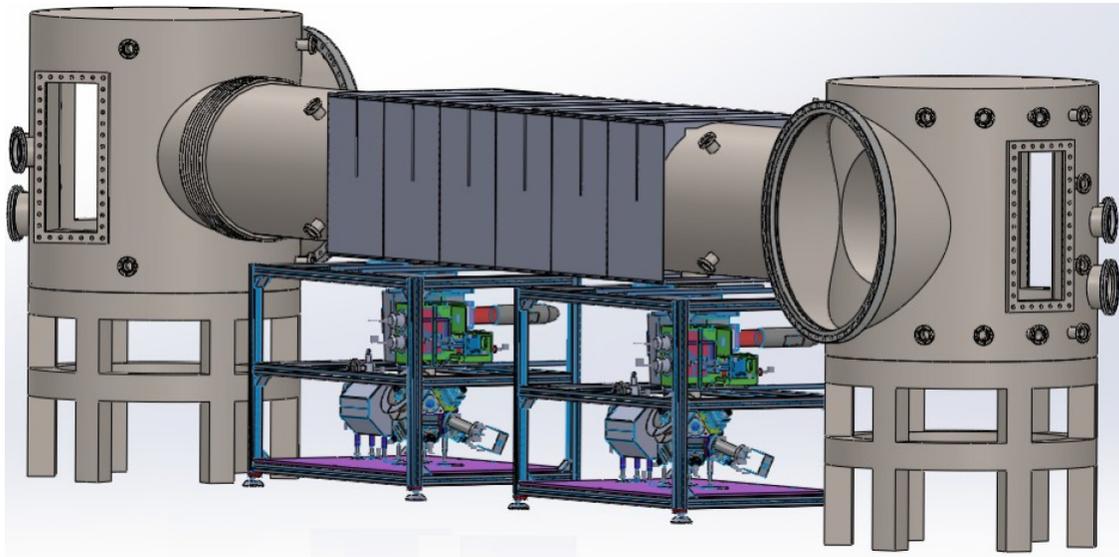


Figure 7: Scheme of the 5 m long baseline gradiometer

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