Upgrade of the detection benches: optics and mechanics

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1 Introduction

The detection of the Virgo dark fringe and secondary beam signals is performed by using a cascade of two benches: the suspended bench and the external bench. The configuration of these benches during the Central Interferometer (CITF) commisioning has been described in [1]. The suspended bench receives the dark fringe (B1) and the secondary beam (B5) reflected by the second face of the beam splitter. The role of the suspended bench is:

- to filter the dark fringe signal
- to reduce the beam waist to about 1 mm to adapt it to the size of the photodiodes
- to separate the two beams B1 and B5

The dark fringe signal is filtered with an Output Mode Cleaner (OMC) [2, 3]. The reduction of the beam waist is performed with a telescope [5].
Since the beam size is different for the whole interferometer (21 mm) from the CITF beam size (3.25 mm), a new telescope had to be designed. This note describes the new telescope design as well as the upgrade and test of the suspended bench. New fonctionalities have also been added on the external bench, these are described in the last section.

2 Upgrade of the suspended bench

2.1 The new telescope

The beam size reduction is more difficult to achieve than for the CITF since it is 7 times larger, moreover there is more risk of introducing aberrations because of the high reduction factor. Special care has therefore been taken in order to reduce the losses with respect to the TEM00 mode.
The new telescope has to fulfill the following criteria:

- reduce the beam waist by a factor 20
- limit the losses on the TEM00 mode to less than 1%
- separate B1 and B5 (inside or after the telescope)
- minimise the modifications on the two benches

These specifications, the possible designs and the final one are discussed in this section.

2.1.1 Specifications

Beam size reduction
In order to keep the other optical components unchanged with respect to the CITF architecture the same type of telescope has to be used: an afocal system, i.e, made of two optical components of focals f_1 and f_2 with f_1/f_2=20 and the distance between the two components is $d = f_1 + f_2$.

Losses

Three type of losses have been considered: spherical aberration, absorption inside the optical components and losses due to imperfect coatings and mismatch of the beam to the output mode cleaner. Since the total loss has to be smaller than 1%, the limit has been set arbitrarily to 0.3% for each type of loss.

1- To reduce the losses due to spherical aberrations of the order of 0.3% the focal length of the first component must fulfill [6]:

   - $f > 0.9$m for a spherical mirror
   - $f > 2.1$m for a plano-convex lens
   - $f > 2.3$m for a bi-convex lens

2- The absorption inside silica is negligible, typical high reflective coating of mirrors is higher than 99.9% and anti-reflective coating of the order of 0.1%.

3- To reduce the losses due to a mismatch of the beam to the OMC below 0.3% the beam incident on the OMC has to fulfill (see annexe A):

   - $\delta w = w - w_0 < 8$ μm where $w_0 = 140$ μm is the OMC caracteristic waist and w the beam waist
   - $\delta z < 6.5$ mm where δz is the distance between the beam waist position and the OMC center.

   δw is directly related to the precision with which the telescope length is adjusted. On the contrary, δz mainly depends on the position of the lens located between the telescope and the OMC.

Separation of B1 and B5

The criteria used for the separation is that the beams overlap is small enough so that losses and diaphony are negligible [7]:

$$d_{B1B5} > 8 \times w \tag{1}$$

where d_{B1B5} is the distance between the two beam centers and w their waist.

Size of the telescope

The new telescope has to fit in the same place as the CITF telescope. If mirrors are used the distance between the two components should be 0.8 m. The only way to increase its size would be to exploit the vertical dimension but this enhances the complexity and introduces the need for mechanical modifications. If lenses are used with planar mirrors the telescope length can be increased up to about 2 m.

2.1.2 Possible solutions

Several systems have been considered, which are described in the following. They make use either of spherical mirrors or parabolic mirrors or lenses.

Spherical mirrors
First the use of spherical mirrors has been envisaged. Due to the large reduction factor small focal length has to be used, leading to non negligable spherical aberrations. If the same sketch as for CITF is used with adapted focal length (0.7 m for the first component)the spherical aberrations lead to losses of the order of one to two percent on the TEM00 mode. Increasing the focal length requires to increase the telescope length, which is very difficult without modifying the whole bench. Moreover the use of inclined spherical mirrors introduces large astigmatism which leads to few percent losses on the TEM00. For these reasons the use of spherical mirrors has been rejected.

Parabolic mirrors
The spherical aberrations can be avoided by the use of parabolic mirrors. Moreover astigmatism is also avoided with the use of out of axis parabolic mirrors. Thanks to these advantages the same sketch as for CITF could be used for the telescope with f_1=0.74 m and f_2=0.037 m.
However, due to the small focal length, the telescope length has to be adjusted with a precision of about 50 μm. Moreover the aberrations are avoided only if the beam is well centered on the two mirrors.

Lenses
If lenses are used, the telescope length is increased since they can be placed at the entry of the bench and just after the prism. Therefore larger focal length can be used. In this case the telescope is 2.2 m long and $f_1 = 2.1$ m, $f_2 = 0.1$ m. If plano-convex lenses are used the loss due to spherical aberrations is only about 0.3% [6].
The two beams are well separated by the prism: their distance is 7 to 9 mm (given the error on the Beam Splitter wedge: $\alpha = 1.10 \pm 0.075$ mrad) for a beam waist of 800 μm.
Since the telescope is longer than with parabolic mirrors, the requirement on the telescope length precision is looser: a precision of 0.5 mm is enough.
The only drawback of this system is the retrodiffusion of light into the interferometer which might introduce seismic noise from the suspended bench. For a plano-convex lens with $f_1 = 2.1$ m and an antireflecting coating of 10^{-3} the fraction of the reflected beam projected on the ITF TEM00 mode is 3×10^{-9} (see annexe A). Therefore the seismic noise introduced is considered to be negligible.

2.1.3 Final design

From this study, lenses or parabolic mirrors can be used for the new telescope. The system with two lenses has been chosen for its simplicity. A schematic of the layout is shown in Figure 1. The total length of the telesccope is $d_{L1L2} = 2.16$ m. There are two planar mirrors inside the telescope (M1 and M2). The telescope length is adjusted with L1 which is mounted on a motorized translation stage and the angular alignment is done with the two mirrors mounted on motorized mounts. The lenses are oriented to minimize the retrodiffusion into the interferometer: as shown in Figure 1 the beam goes first through the convex face of L1, the planar face of L2 and the convex face of L3.
The two beams are separated inside the telescope with the prism, therefore there are two lenses L2 (one on each beam).

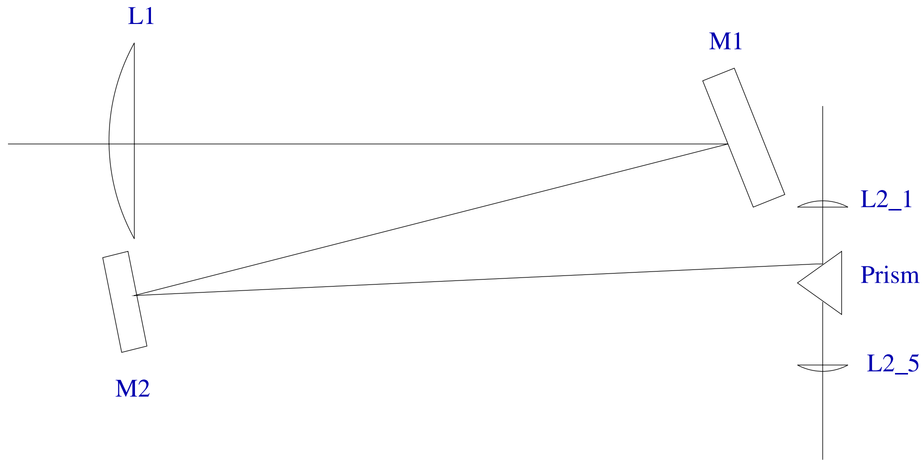

Figure 1: *Schematic view of the new telescope (not to scale). Only the path of B1 is shown.*

The characterisitcs of the optical components are listed in Table 1. The coatings of the lenses and mirrors have been made in IPN-Lyon. The losses due to spherical aberrations is of the order of 0.3%, and the total loss by absorption and due to imperfect coating about 1% ([8], the main source of loss is the imperfect coating: about 0.3% for L1 and 0.1% for the mirrors and L2).

name	type	material	focal length (mm)	diameter (mm)	thickness (mm)	coating
L1	plano-convex lens	silica	2059±3	120	12	AR: $R \simeq 3 \times 10^{-3}$
L2	plano-convex lens	silica	104.4±0.1	25	3	AR: $R \simeq 1 \times 10^{-3}$
M1	planar mirror	BK7	-	80	15	HR: $R > 0.999$
M2	planar mirror	BK7	-	50	10	HR: $R > 0.999$

Table 1: *Characteristics of the optics used for the new telescope. The coatings characteristics have been measured in IPN-Lyon.*

2.2 Modifications of the bench

The upgraded bench is shown in Figure 2. This section describes the modifications made to the bench.

2.2.1 Telescope

The telescope described in the previous section has been installed on the suspended bench (see Figure 2). The lens L1 sits on a motorized translation stage. The prism support has been modified in order to support the two lenses L2. The position of these two lenses can

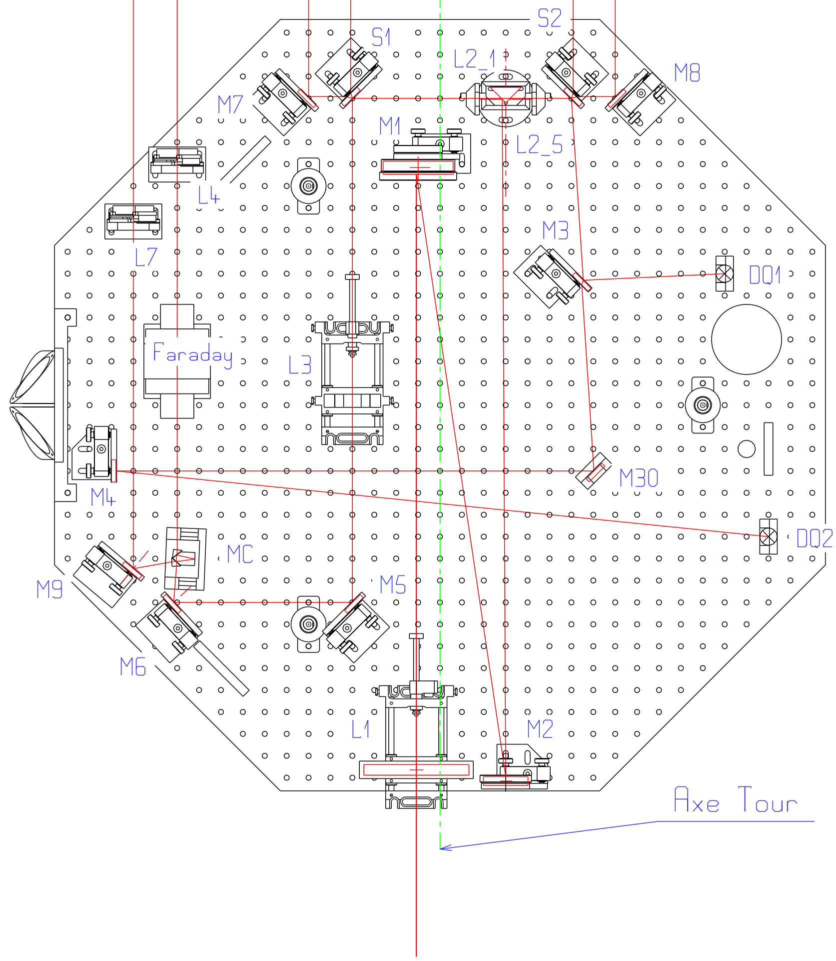

Figure 2: *Layout of the suspended bench*

be manually adjusted.

The lens L3 has also been equiped with a motorized translation stage in order to allow the adaptation of the beam waist position with respect to the OMC.
The translation stages have been made in LAPP and are equiped with picomotors. The full displacement is about 4 cm. Special mounts have also been done for all these optics.

2.2.2 Faraday isolator

A Faraday isolator has been added after the OMC in order to avoid reflection from the external bench into the interferometer. It is a Linos Photonics product (ref: FR 1060/8 HP VF) using a TGG crystal ($n = 1.95$) as rotator and two polarisers.
Its transmission has been measured with a powermeter: $T_{Faraday} = 96\%$. The isolation is better than 30dB (from the producer data sheet).
The Faraday isolator translates the waist position by $e(1 - \frac{1}{n})$ where e is the Faraday crystal length and n its index (the same applies to the polarisers but the effect is smaller since they are smaller and have lower index). The crystal size is not known precisely (few centimeters) but measurement of the beam size with and without Faraday confirms that the waist is displaced by 1.5 to 3 cm towards L4. The lens L4 has therefore been moved by 2.5 cm towards the external bench.

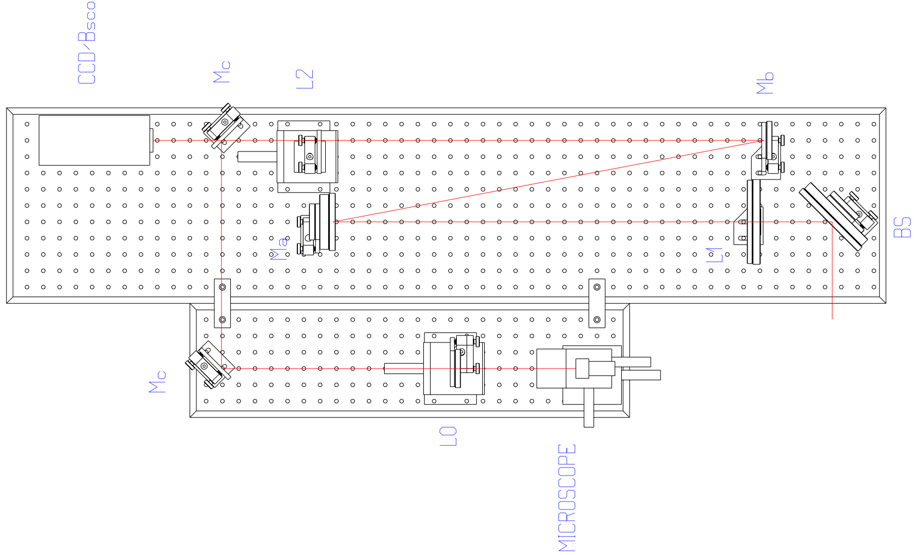

Figure 3: *View of the test bench*

2.2.3 S1 and S2 mirrors

The mirrors S1 and S2 which were of poor quality have been replaced by new ones. The mirror S1 (silica) extracts a small fraction of B1 before the OMC leading to B1p beam. The transmission of S1 has been measured (for s-polarisation): $T_{S1} = (0.55 \pm 0.05)\%$. The mirror S2 (BK7) extracts a fraction of B5 which is sent to the quadrant photodiodes DQ1 and DQ2. The reflexion of S2 to the quadrants is $R_{S2} = (7.8 \pm 0.5)\%$ and its transmission $T_{S2} = (91 \pm 1)\%$ (for s-polarisation).

2.3 Tests of the upgraded suspended bench

The suspended bench has beam modified as described in the previous section in the Virgo clean room in autumn 2002. Several tests have been made in that clean room which have been completed when the bench was put back inside the tower (winter 2002-2003).
In order to test and adjust the new telescope a Virgo-like beam has been generated with the test bench located about 1 m before the suspended bench.
In this section the test bench is described, then the tests and adjustememts performed on the suspended bench are discussed.

2.3.1 Test bench

The test bench is shown in Figure 3. For the tests inside the tower this bench is placed in front of the detection tower (at the Brewster's link place), as shown in Figure 4. The s-polarised laser beam is sent from the detection laboratory through an optical fiber [1]. Its waist is increased to 1 mm thanks to a microscope and a first lens. Then a telescope similar to the suspended bench telescope used in reverse direction increases its waist to 21 mm. The length adjustment of this telescope has been made in the following way: since it is not possible to measure the beam waist and check if the beam is parallel after

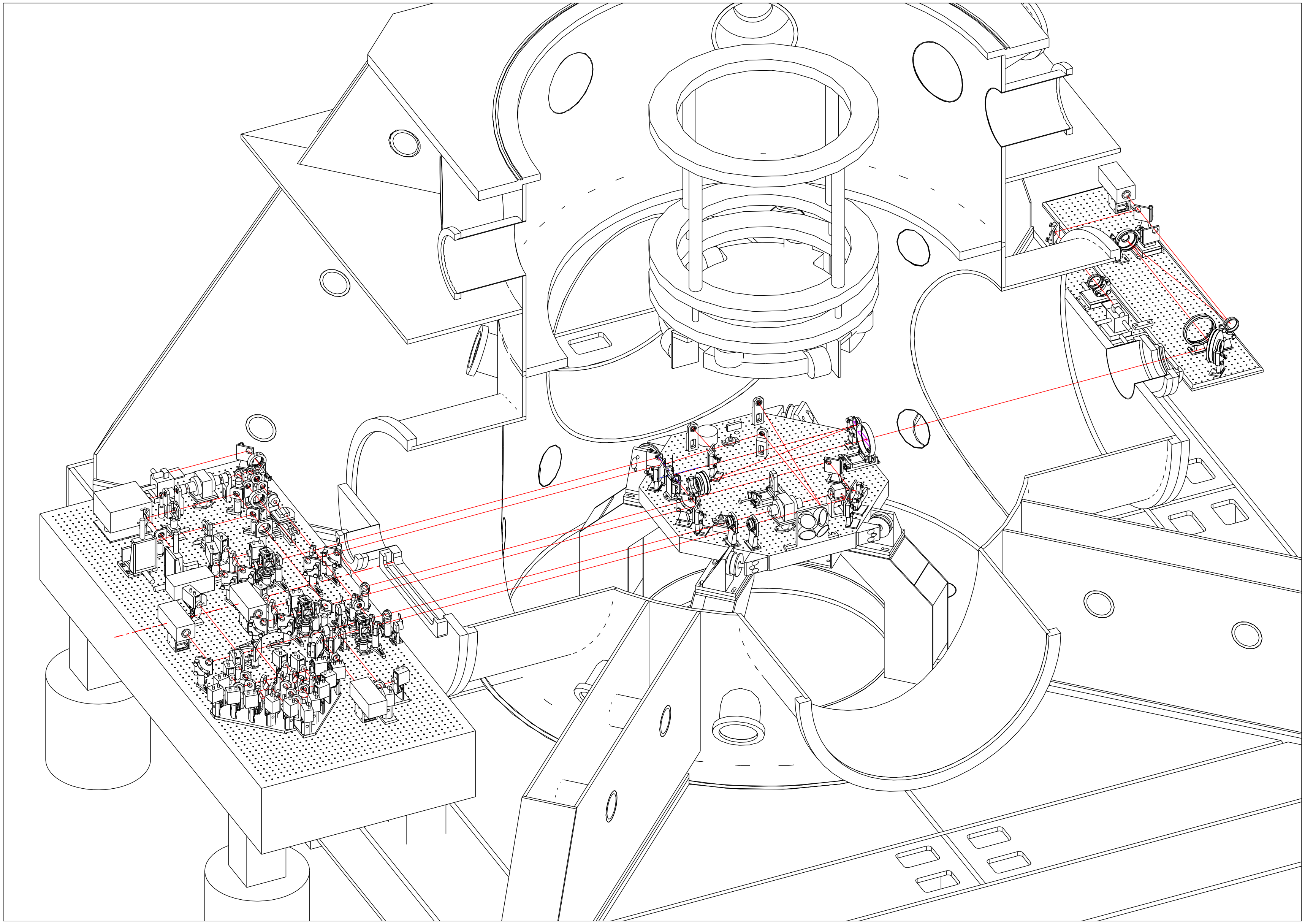

Figure 4: *View of the suspended (center) and external (right) benches and of the test bench (left)*

the telescope, a planar mirror is placed perpendicular to the beam after the telescope so that the beam is sent back through the telescope. The size of the reflected beam is measured after the telescope. The telescope length is well adjusted when the reflected beam is identical to the input beam (i.e. parallel beam of waist $w_0 = 1$ mm). With this method the precision on the output beam waist is 5%.
The last optical element of the test bench is a dummy beam splitter (a BK7 non-parallel faces plate with a wedge of 1.1±0.1 mrad an a thickness of 15 cm) which allows to create two beams separated by 3.8 mrad similarly to B1 and B5.

2.3.2 B1 and B5 separation

The distance between B1 and B5 has been measured with a decimeter few milimeters before the prism. It is 9.0 ± 0.5 mm, as expected. Since the beam size is around 0.8 mm two beams are very well separated.

2.3.3 Telescope length adjustement

First, the position of the two L2 lenses have been manually adjusted so that they are located at the same distance from L1. Since the optical path of B1p and B5 is the same, the size of these beams should be identical. The waists of B1p and B5 are measured by the external bench CCD cameras and the position of the lens L2 which is situated on B1 path is adjusted until the two waists are equal.
Then the position of L1 is adjusted so that B1p and B5 size matches the expected size. Figure 5 shows the beam profile of B5 or B1p from L1 to the CCD located on the external bench. This beam profile is computed using the gaussian beam propagation. After this adjustment the size measured by the CCDs is (600 ± 40) μm. The uncertainty on this measurement comes from a set of several measurements. The precision on the telescope length is deduced from the uncertainty on this measurement: $\delta d_{L_1L_2} = 0.5$ mm (this takes also into account uncertainty on the CCD and L5 position and on L5 focal length).

2.3.4 Matching of the beam to the output mode cleaner

Figure 6 shows the beam profile of B1 from L1 to the CCD located on the external bench. The beam is matched to the OMC in the following way:
After the telescope the beam waist is equal to 1 mm and the beam is almost parallel. The lens L3 ($f = 450$ mm) transforms this parallel beam into a convergent beam of waist $w_0 = 140$ μm located 450 mm from L3, i.e. at the center of the OMC. Since the beam is parallel before L3, the position of L3 has almost no impact on w_0. Therefore w_0 is only influenced by the telescope length. The precision on the telescope length (0.5 mm) corresponds to an uncertainty on the beam waist after L3 of $\delta w = 1.5$ μm and therefore to OMC losses lower than 0.1% (see annexe A).
The position of L3 has to be adjusted in order to position the beam waist at the center of the OMC. At first order the beam waist displacement is equal to L3 displacement. The requirement on L3 position is not very strong since a δz of 10 mm leads only to losses of 0.7%. The adjustment consisted in maximizing the OMC transmitted power.The size of B1s on the CCD can also be used as a check.
Figure 6 shows the beam profile of B1s from L1 to the CCD located on the external bench.

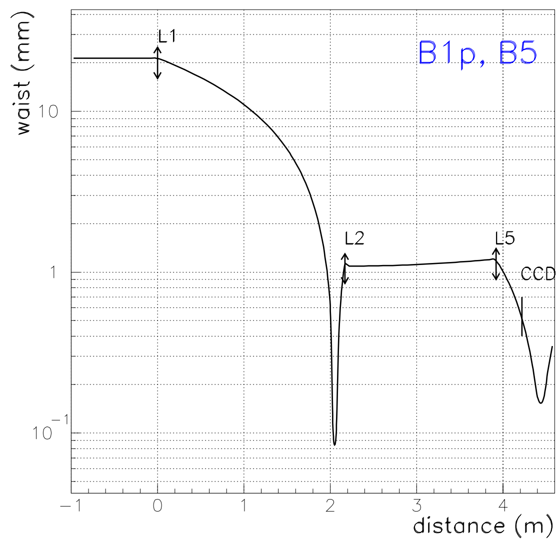

Figure 5: *Profile of B1p and B5 beams from L1 to the external CCD. The photodiodes are located at the same distance as the CCD.*

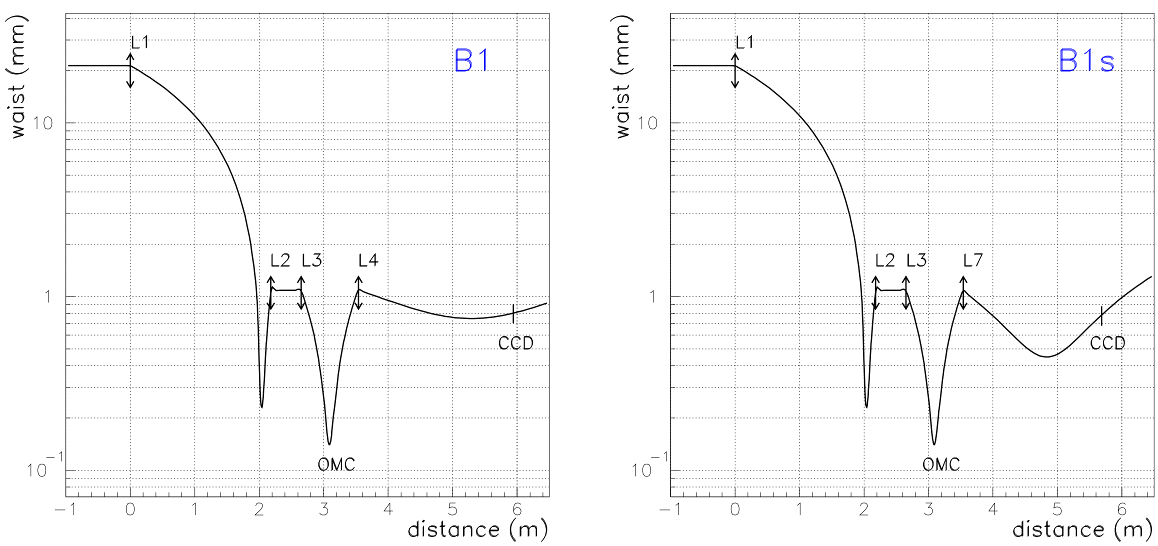

Figure 6: *Profile of B1 and B1s beams from L1 to the external CCD. The photodiodes are located at the same distance as the CCD.*

After the adjustement of L3 position, the size of B1s and B1 are $w_{B1s} = 800 \pm 20$ μm and $w_{B1} = 820 \pm 20$ μm as expected and the maximum measured OMC transmission is 95%. The transmission is given by: $\frac{P_{B1}}{P_{B1s}} \frac{1}{T_{faraday}}$ where P_{B1} and P_{B1s} are the s-polarisation power of B1 and B1s measured on the external bench and $T_{faraday}$ is the transmission of the faraday isolator. These losses are mainly not due to the telescope and L3 adjustement: First there is some intrinsic loss of few percent inside the OMC. Moreover some loss is expected since the input beam is not gaussian. This is due to the fact that the dummy beam splitter is too small with respect to the beam: its effective horizontal radius is less than twice the beam waist, therefore the beam is troncated in the horizontal direction.
Since the Virgo beam might be different from the test beam the positions of L1 and L3 might have to be retuned with the real beam.

2.3.5 Alignment of the telescope with the quadrants

The beam B1 has also to enter the OMC with the correct position and angle. To reduce the losses below 1% the maximum displacement and tilt allowed are [9]:

$$\delta r_{MC} < 14 \mu m \qquad \text{and} \qquad \delta\theta_{\text{MC}} < 240 \mu\text{rad} \tag{2}$$

Since the position of B1 is directly related to the position of B5, this last one can be used to realign the beam on the OMC. The position of B5 is measured with two quadrant photodiodes (DQ1 and DQ2) [10]. Since the optical paths from the telescope output to the OMC and to the quadrants have not changed with respect to the CITF bench configuration, the matrix relating the B5 position measured on the quadrants (x_1, x_2, y_1 and y_2) to B1 position with respect to the OMC (δr_{MC} and $\delta\theta_{MC}$) has not changed:

$$\begin{pmatrix} \delta r_1 \\ \delta r_2 \end{pmatrix} = \begin{pmatrix} 0.93 & -0.45 \\ 3.93 & -0.45 \end{pmatrix} \begin{pmatrix} \delta r_{MC} \\ \delta\theta_{MC} \end{pmatrix} \tag{3}$$

where r_i is equal to x_i or y_i. Therefore the threshold on the asymetries to keep losses lower than 1% are the same: 0.025. The value of the asymetries are used to align the telescope mirrors M1 and M2. The same algorithm [9] as for CITF is used. But since the telescope has changed the calibration factors which relate the asymetries to the number of steps sent to M1 and M2 picomotors have been remeasured and updated. The performances of the algorithm with the new telescope are good. An example of an automatic alignment is shown in Figure 7.

3 The external bench upgrade

The external bench is shown in Figure 8. No major modification has been done to this bench, only few elements have been added:

- Polariser cubes:
  the p-polarisation is separated from the s-polarisation with polariser cubes so that the main photodiode measures only the s-polarisation. Special supports have been made at LAPP (see Figure 9). The height and the tilt of the polariser is adjustable.

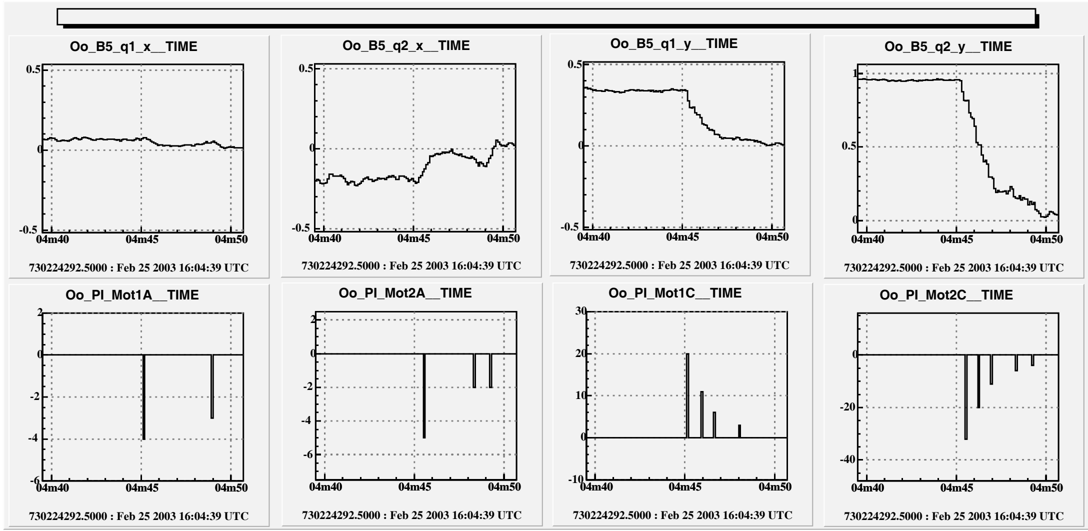

Figure 7: *Example of an automatic alignment of the telescope. The top plots show the horizontal asymetries (left) and the vertical asymetries (right) for the two quadrants (q1 and q2). The bottom plots show the number of pulses sent to the picomotors MotiX where i refers to the mirror number (M1 or M2) and X refers to the motor type (A = horizontal, and C = vertical). In this example the threshold on the asymetries is set to 0.05 (when this value is reached, the alignment is stoped).*

The photodiodes situated on top of the cubes measure the p-polarisation (DC measurement only). The efficiency of these photodiodes is 0.38 A/W. An attenuator can be added between the cube and the photodiode if the power exceeds the photodiode limit (40mW). The photodiodes have an active area of 1cm^2 (Hamamatsu ref. S3590-05). They are inclined by about 10 degrees in order to avoid reflexion back to the interferometer. The signals are readout at 50Hz with an adjustable gain electronic board: there are four gains, the lowest gain is $R_1 = 100\Omega$ and the three others gains are related to each other by $R_i = 20 \times R_{i-1}$.
No p-polarisation measurement is done on B1 since this polarisation is already rejected by the Faraday isolator.

- Readout of the signal at twice the modulation frequency:
  a fraction (not yet fixed) of B5 and B1 beams is extracted and sent on photodiodes equiped with electronics which extract the signal at twice the modulation frequency. These photodiodes are similar to the standard detection photodiodes: they have a diameter of 3 mm and a conversion factor of 0.74 A/W. These photodiodes are positioned so that the optical path is the same as the optical path up to the standard photodiodes. The electronic boards will be described in another note.

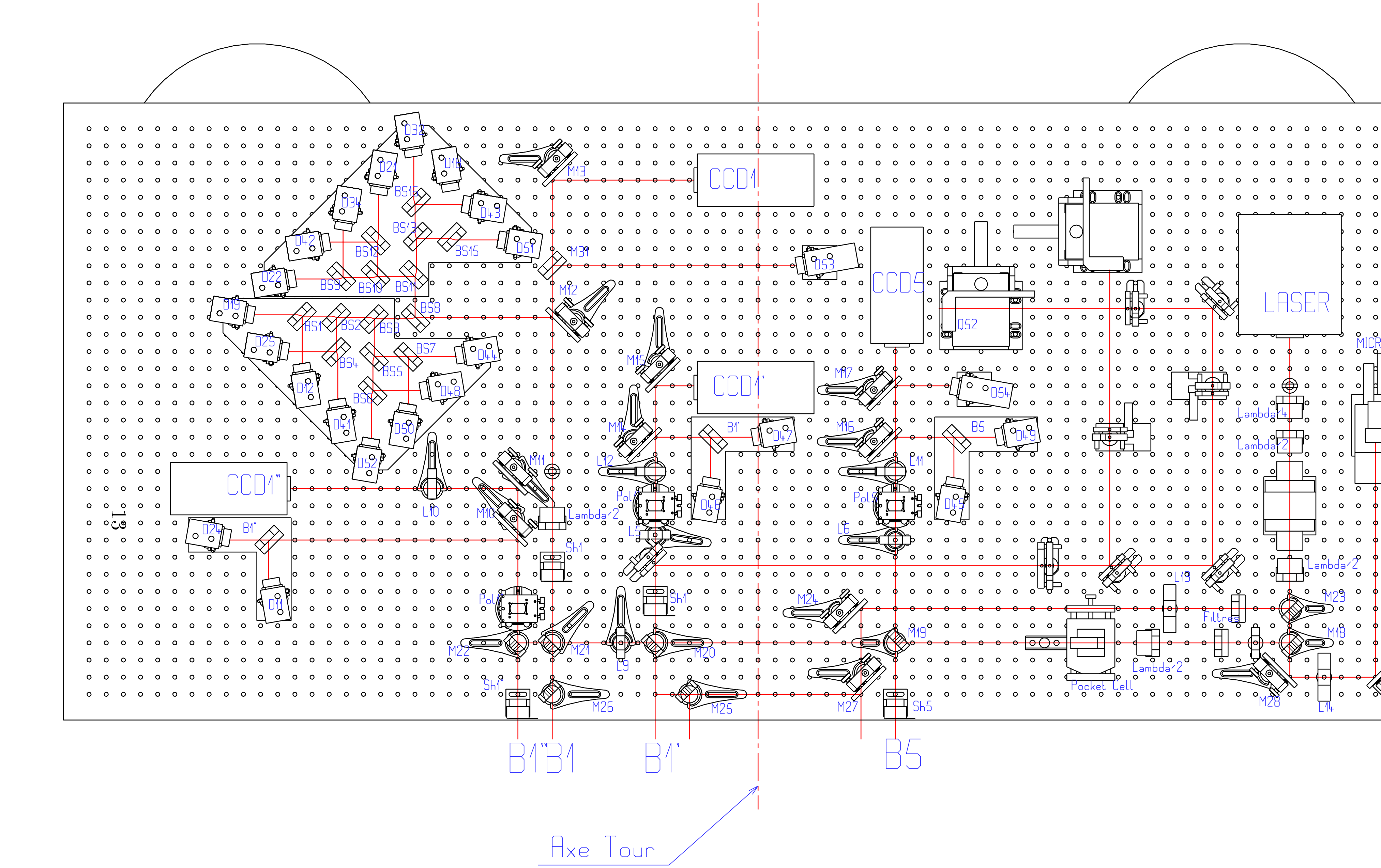

Figure 8: *Layout of the external bench*

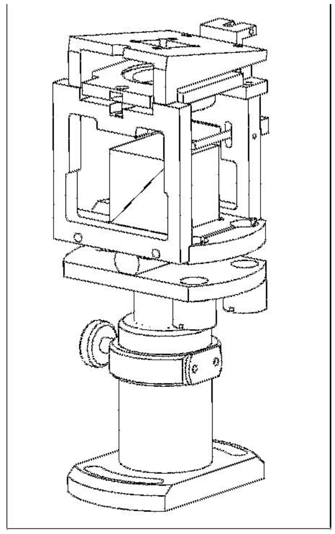

Figure 9: *View of a polariser support for p-polarisation readout (the strings are not shown).*

4 Conclusion

The new telescope is an afocal system based on two lenses. The main source of loss of this system is the imperfect coating of the optics (1% in total). Motorised translation stage have been added in order to help the alignement with the Virgo beam. A test beam has been used to align the suspended bench optics. Once the system is well aligned, the OMC transmission is found to be at least 95% for the TEM00.
A Faraday isolator has been added after the OMC in order to prevent reflection into the interferometer.
New fonctionnalities have also been implemented on the external bench: readout of p-polarisation on all the beams (except B1) and the readout of the signal at twice the modulation frequency.

A Annexe: Losses due to a beam mismatch

A beam field $|\Psi>$ is defined by $|\Psi>=|\Psi_x>|\Psi_y>$ with

$$|\Psi_x>=\left(\frac{2}{\pi}\right)^{1/4}\frac{1}{\sqrt{w_x}}e^{-x^2\left(\frac{1}{w_x^2}+i\frac{k}{2R_x}\right)} \tag{4}$$

where R_x is the beam radius of curvature and w_x is the beam waist.
The losses with respect a TEM_{00} characterised by w_0 et R_0 are defined by:

$$\mathcal{L}=1-|<\Psi|w_0,R_0,0>|^2 \tag{5}$$

with

$$|<\Psi|w_0,R_0,0>|^2=|C_x|^2|C_y|^2 \tag{6}$$

$$|\mathrm{C_x}|^2 = \frac{4|\mathrm{R_0 R_x}|\mathrm{w_x w_0}}{\sqrt{4\mathrm{R_0^2 R_x^2}(\mathrm{w_x^2}+\mathrm{w_0^2})^2 + \mathrm{k^2}(\mathrm{R_x}-\mathrm{R_0})^2 \mathrm{w_x^4 w_0^4}}} \tag{7}$$

If $\mathrm{R_0}$ is infinite:

$$|\mathrm{C_x}|^2 = \frac{4|\mathrm{R_x}|\mathrm{w_x w_0}}{\sqrt{4\mathrm{R_x^2}(\mathrm{w_x^2}+\mathrm{w_0^2})^2 + \mathrm{k^2 w_x^4 w_0^4}}} \tag{8}$$

Therefore (if w_0 and w_x are of the same order),

$$\mathrm{kw_0^2} << 2\mathrm{R} \Rightarrow |\mathrm{C_x}|^2 = \frac{2\mathrm{w_x w_0}}{\mathrm{w_0^2}+\mathrm{w_x^2}} \tag{9}$$

$$\mathrm{kw_0^2} >> 2\mathrm{R} \Rightarrow |\mathrm{C_x}|^2 = \frac{4|\mathrm{R_x}|}{\mathrm{kw_0 w_x}} \tag{10}$$

1- Case of a mode cleaner mismatch

If the beam is not astigmatic the loss is

$$\mathcal{L} = 1 - \frac{16\mathrm{R^2 w_0^2 w^2}}{4\mathrm{R^2}(\mathrm{w^2}+\mathrm{w_0^2})^2 + \mathrm{k^2 w^4 w_0^4}} \tag{11}$$

with the mode cleaner waist $w_0 = 140\mu$m.
If R is infinite and $w = w_0 + \delta w$ (waist mismatch):

$$\mathcal{L} = 1 - \frac{4\mathrm{w_0^2 w^2}}{(\mathrm{w^2}+\mathrm{w_0^2})} = \left(\frac{\delta \mathrm{w}}{\mathrm{w_0}}\right)^2 \tag{12}$$

If R is finite (waist position mismatch) and $w = w_0$:

$$\mathcal{L} = 1 - \frac{1}{1+\frac{\mathrm{k^2}}{16\mathrm{R^2}}\mathrm{w_0^4}} = \left(\frac{\mathrm{kw_0^2}}{4\mathrm{R^2}}\right)^2 = \left(\frac{\mathrm{z_R}}{2\mathrm{R}}\right)^2 \tag{13}$$

with $z_R = \pi w_0^2/\lambda = 58$mm.
If the beam waist position is close enough to the mode cleaner (i.e. $\delta z << z_R$) then $R = \frac{z_R^2}{z}$ and

$$\mathcal{L} = \left(\frac{\delta \mathrm{z}}{2\mathrm{z_R}}\right)^2 \tag{14}$$

2- Case of the retrodiffusion on L1

The beam retrodiffused by the first face of the plano-convex lens is characterised by $R_x = R_y = 0.5$ m (the radius of curvature of that face is 1 m) and $w_x = w_y = 2$ cm. The projection of this beam on the ITF $\mathrm{TEM_{00}}$ is (in this case $kw_0^2 >> 2R$):

$$| < \Psi|\mathrm{w_0}, \mathrm{R_0}, 0 > |^2 = \frac{16\mathrm{R^2}}{\mathrm{k^2 w^2 w_0^2}} = 0.6 \times 10^{-6} \tag{15}$$

The beam reflected by the second face of L1 is characterised by $R_x = R_y = 1$ m and $w_x = w_y = 2$ cm (it acts as a bi-convex lens with a focal of 1m), therefore

$$| < \Psi|\mathrm{w_0}, \mathrm{R_0}, 0 > |^2 = 2 \times 10^{-6} \tag{16}$$

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