The pre-alignment of the VIRGO 3-km interferometer

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Introduction

The goal of the prealignment procedure of the 3-km VIRGO interferometer was to obtain a positioning and orientation of all the mirrors, beams and optical elements of the entire detector, in order to allow the starting of the activities for the longitudinal locking of the optical cavities.
The specifications on the prealignment of the suspended masses have never been explicitly defined. An alignment of the mirrors, with respect to the interferometer axis, of less than some tens of μrad, and a centering of the beam on the mirrors of some millimeters on the PR mirror and within one centimeter on the other mirrors, have been considered reasonable requirements for starting interferometer operations. These conditions have actually turned out to be sufficient for the further locking activities.
In the final prealignment phase the Local Controls (Ref.1) were working on all the suspended masses, so that a controlled adjustment of the mirror orientation at the μrad level was possible.

1. Foreword: Tower positions and vacuum tubes

1.1. Starting specifications

The first step in defining the VIRGO geometry has been the geometry computations for the tower positions in the CITF (hereafter referred as "CITF reference system"). This computation has been carried out according to the optical properties of the beam splitter (cfr. Ref. 2 and Ref. 3). These properties define the orientation of the North and West arm one with respect to the other. The optical properties of the Beam Splitter are:

- A small angle of 1.1 mrad between the two faces, the opening of which looks toward the terminal mirrors constitutes the wedge of the Beam splitter.
- The beam splitter thickness at its center is 55 mm.

In the document "Virgo geometry reference system" (crf. Ref. 3) the GPS measured coordinates and altitudes are taken with respect to an ideal ellipsoid called WGS84. The gravity field (i.e. the geoid) was estimated in the Virgo site, and has just a slope with respect to the ellipsoid. This document gives the coordinates of all the towers with respect to the "Virgo General Reference System" (VGRS), a local Cartesian system. Its vertical axis is the local vertical given by the gravity field, at the vertical of the crossing of the Virgo North and West light beams.,"very near the center of the Beam Splitter tower"…

Taking this into account, the surveyors have positioned the tubes and towers accordingly to the draft version of Ref. 4 ("L'allineamento dei tubi a vuoto : Installazione e rilievo della rete dei punti di riferimento"). As stated in this document, the vacuum tubes alignment has been carried out using the following references:

- 22 GPS points: one each 300m from the input towers until the end towers in West and North arms. Their coordinates are given with respect to the WGS84 earth reference system. When positioning this points with respect to several antennas, an accuracy of : +/-2mm in a plan, +/-5mm in altitude is achieved.

- 200 reference points in each arm every 15m.

The angles (in the horizontal plane) between the interferometer axis result are shown in Fig. 1.3-1. The deviation induced in the BS is then 26.77 mm on the center of the injection bench and 23 mm on the PR.

Some tolerances on the deviation of the beams are the following: let's call $\pi/4-\varepsilon$ the incident angle on the Beam Splitter, with ε being the difference from angle $\pi/4$ of the incidence angle of the input beam. The nominal position is ε=0.435mrad. Varying ε induces $\pi/2+2\cdot\varepsilon$ on the angle between the North and West beams and $0.0014\cdot\varepsilon$ the angle between input and North beam. This means that in a first approximation, varying the incidence of the input beam (ε) or the Beam splitter induces the same variation on the North Beam and twice the variation on the reflected beam as for a BS without wedge.

For the beam to reach the NE mirror, the angle between the beam transmitted by the BS and the north direction has to be not larger than 100 μrad. Since the distance between the IB and the BS is about 12 m, this means that an accuracy of $100\ \mu\text{rad}\cdot 12\text{m} \approx 1$ mm in the positioning of the starting point of the beam injected in the ITF on the IB is required.

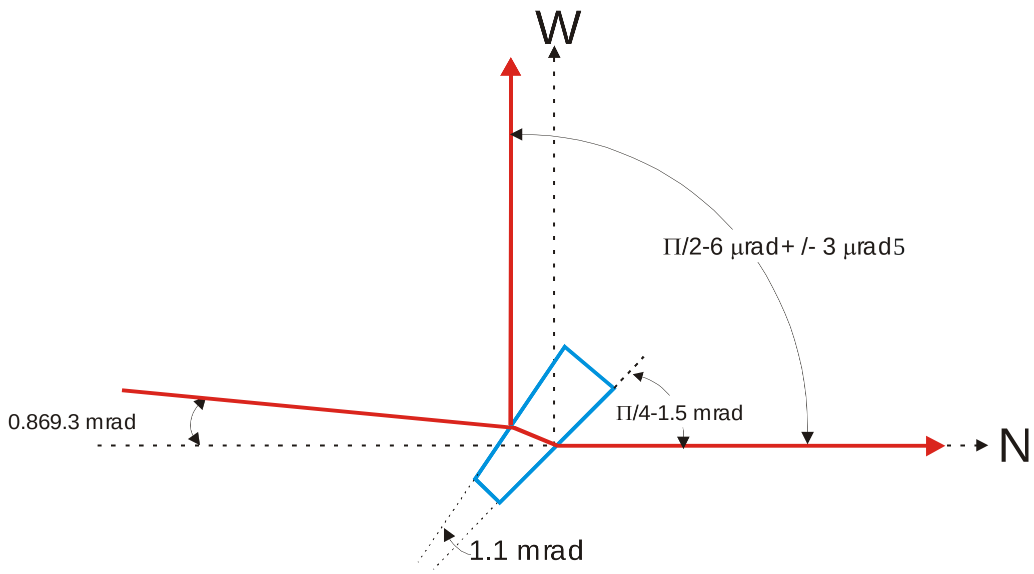

Fig. 1-1

According to surveyors evaluations, the North Arm and the West Arm do not lie exactly on the same plane, the distance between the two planes at the level of the BS being about 7 mm. The angle between the North and West arm, as evaluated between the projections of the two arms on a plane parallel to both arms, is α=99.999640g = π/2-5.6 μrad, with at a 2.8 μrad accuracy. As a consequence, the angle between the North and West arm appears to be (almost) exactly π/2 (the positioning of the BS wedge was decided using a reference engraved on its edge. The accuracy of this positioning was about 0.5 mm/200 mm = 2.5 mrad).

1.2. Position of the CITF towers (in the CITF reference system)

In **Fig. 1.3-1** the actual position of the towers measured, in the CITF reference system (cfr. Ref.2) is reported.

A slight difference in the position of some towers, with respect to the designed specifications, has been detected. These positions have to be taken into account when deciding the positioning of the mirrors.

1.3. Agreement between CITF reference system and tunnel reference system

For the positioning of the North and West arms 2 reference points distant ~15 m are taken as first references: the first points are close to the input mirror towers, the second ones are in the old workshops, at the start of the tunnels. The central building reference system had been settled previously than the arms reference system. Hence, the two reference systems shouldn't be correlated better than 1mm/15m=67μrad. If the benches in the towers have been positioned with a mm accuracy, and if the memory position system recovers the previous position of the payload up to the mm, we can say that the central payloads are within +/-3mm of their designed position in Ref. 3.

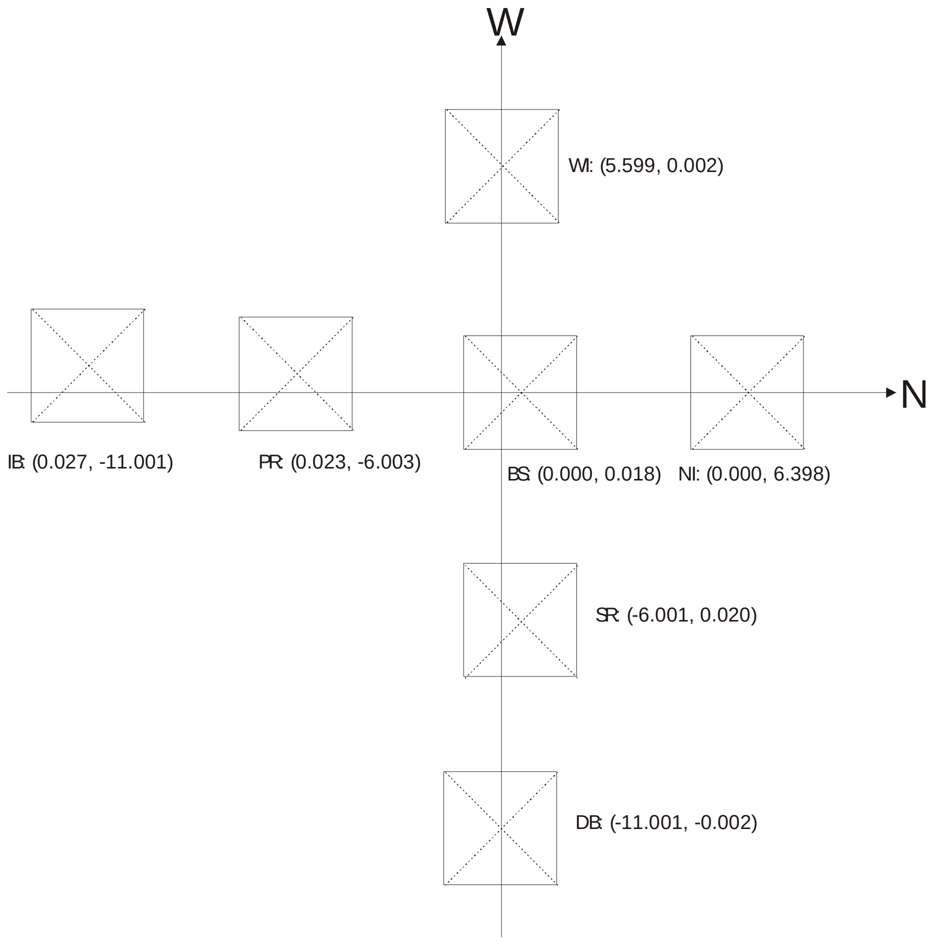

Fig. 1.3-1 *CITF tower positions in VIRGO*

2. VIRGO mirrors prealignment

2.1. Alignment of the tower and of the separating roof:

All the suspensions have been installed and prealigned in the Virgo VGRS system. The prealignment of the payloads has been defined using the following procedure:

1) A marker on the floor is placed in the CITF reference system: this is the center of the tower.
2) The basis of the tower is placed around this marker: the square flange (which is on the basis of the tower) has markers at its corners. The crossing of the diagonals connecting these markers is above the marker on the floor (precision about 1 mm).
3) The separating roof is installed: the wall supporting the separating roof leans on the basis of the tower. The separating roof, at the end, is below the square flange.
4) A tool supported by two wires is hanged to the separating roof: the tool is an approximately cross shaped flange, having a hole in its center. On the arms of the cross four markers are visible. The length of the two wires is accurately defined, such that the center of the hole is at the height of the final mirror. The markers on the cross are approximately placed, with respect of the center of the hole, were the markers of the mirrors will be visible.
5) Using a theodolite (as an autocollimator) the separating roof position is adjusted: by looking at the markers its position plane is adjusted; by looking at the reflection by a mirror in the hole

the θ_y angle is adjusted. The markers on the ground are fixed using the GPS references established in the tunnel. The height of the separating roof is defined with an optical level.

6) At this point the separating roof and the tool are placed, so that markers and mirror are placed and oriented as the final mirror will approximately be.
7) The local controls camera is installed: its position is defined by fixed references rails, so that, even when removing the camera, it can be later reinstalled in the same position.
8) After installation of the camera, an image of the tool is acquired by the Gx[1]. This image will be used as future memory reference also for the mirrors. Therefore, since the image is referred to the chip of the camera, the memory reference is in practice decided by the reference rails for placing the camera in its position: if these references rails are moved or displaced for some reasons, the memory reference is of no use any more.
9) In the NE, after having taken the memory image, it has been compared with the markers of the dummy mirror installed after the assembling of the tower: the two images were in good agreement.
10) The position of the separating roof and the Gx memory image is later used for the positioning of the payload.

In conclusion, the positioning of all the payloads is referred to the Gx, which is referred to the theodolite positioning and the tower positioning, which have as a reference the CITF reference system. It is therefore important to be sure that the CITF reference system is coherent with the tunnel reference system.
A check of the agreement between the central building reference system (CITF reference system) and the tunnel reference system has been done. The position of all the marker reference points in the central building has been checked again using a theodolite total station. The position of the center of the PR tower and of the axis PR-Input Towers has been verified to be in agreement with the past measurement in the CITF. To check the agreement between the central building reference system and the arms reference system, the positions of some reference markers inside the tunnels (1-2-3-4-5-6-GPS-50-100 for each tunnel) have been measured, starting from the references in the central building. However, the most significant measurements, those relative to the markers 50 and 100 inside the tunnels, were very variable (the RMS was larger than the theodolite specifications). Therefore, this measure cannot be taken as conclusive.

2.2. Power Recycling mirror positioning

The first important issue arising in the prealignment of the mirrors along the laser beam originates from the curvature of the PR mirror: the PR mirror is a plane-convex lens, the plane face being the one reflective for Nd:Yag and closer to the BS, the convex one AR for Nd:YAG and closer to the IB. The curvature radius of the curve face is about 4.3 m (focal length of about 9.555 m for λ=1.064 μm). An off center of 1 mm of the beam with respect to the center of the PR mirror results in a 100 μrad angle with respect to the normal to the plane face (cfr. Ref. 5). At 3 km, this implies 30 cm of displacement. As a consequence, the beam has to be centered with respect to the PR mirror better than a mm. Since the curve face of the PR is AR for the Nd:YAG, it is very difficult to understand whether the incidence is centered or off centered. Using another wavelength allows to distinguish between the two reflections from the two faces of the PR, thus allowing to understand the centered or off centered position.

[1] The Gx is the software for elaborating the image of the mirrors acquired by the CCDs (cfr Ref.1).

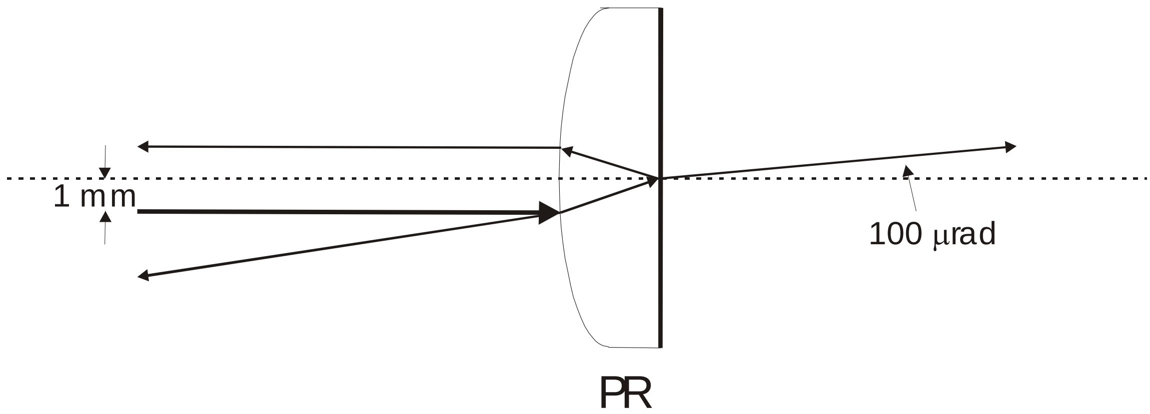

Fig. 2.2-1:*The PR mirror and the angular deviation due to a transversal displacement of the beam*

2.2.1 North Axis definition: HeNe without PR mirror and Brewster link

As a first step, a HeNe beam has been sent to the North End before the PR mirror was installed. The beam was collimated in order to obtain a spot of about 20 cm diameter at the NE. The whole arm (PR-NE, including tube) was in vacuum. The Brewster link between the Injection Tower and the PR tower had been removed. The beam was injected in the PR vacuum chamber through an uncoated window.

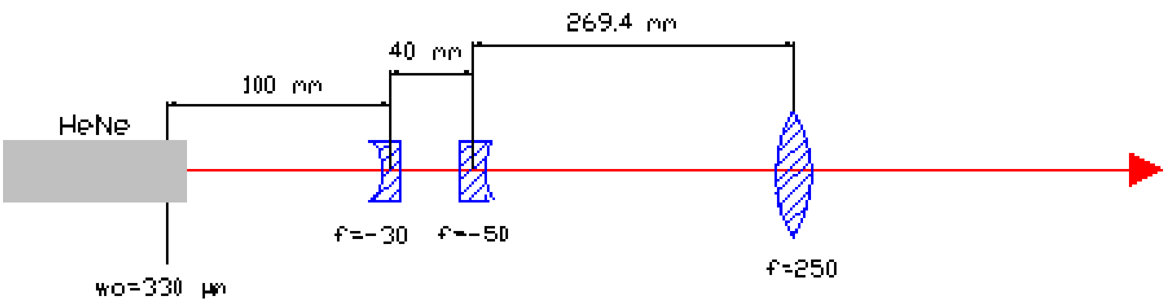

Fig. 2.2-2: *The HeNe beam and the telescope used to send the beam to the NE (without PR mirror installed).*

Once the light spot had been detected at the NE, the error on the angle between the North Axis and the HeNe beam was less than 30 cm/3 km, (30 cm being about the NE output window diameter and 3 km its distance from the HeNe laser), i.e. 100 μrad.

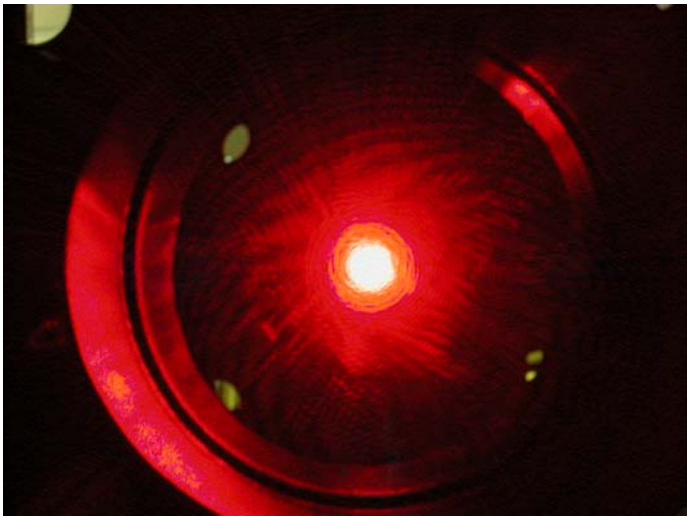

Fig. 2.2-3: *First light transmitted from the Central Building to the NE (an HeNe beam): the picture was taken from the NE window looking inside the tube.*

2.2.2 PR mirror installation

The beam was then left aligned in this position, and the PR mirror was installed inside the payload.

The PR mirror is mounted inside the dummy glass mass in such a way, that the plane face is 2 cm from the back side of the dummy glass mass, and the gravity center of the whole mass (rotation axis of the payload) is on the vertex of the curved surface of the PR mirror (thickness of the curved mirror: 3 cm, thickness of the dummy glass: 10 cm).

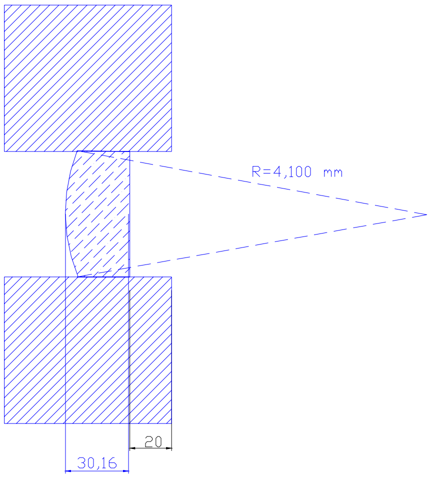

Fig. 2.2-4: *The PR mirror inside its fused silica housing as mounted in the payload.*

We started from a condition in which the HeNe beam had been aligned along the North axis with a precision better than 100 μrad. The HeNe beam had been prealigned without the PR mirror in place (see 2.2.1). Then the PR mirror was installed, and we looked at the reflection from the two faces of the mirror.

The PR mirror is rotated using the marionetta Local Controls until the reflection from the plane face is autocollimated with the incident beam. We first autocollimated the HeNe beam reflected by the plane face of the PR on the HeNe laser itself. Then, the distance Y between the beam reflected by the curved face and the beam reflected by the plane face (autocollimated with the incident beam) was measured. Knowing the PR radius R of curvature (about 4100 mm), the distance L between the PR, the plane where we make the measurement was made (about 3000 mm) and the fused silica refraction index for HeNe (1.457), by measuring Y in this condition it is possible to reconstruct the angle θ_X and θ_Y of which the PR mirror was rotated with respect to the HeNe direction of incidence (that is the North axis) and the translation *a* of the mirror with respect of the same axis. To measure the distance Y between the two spots an iris diaphragm was used: the incident beam and the beam reflected by the plane face passed through the diaphragm hole, the beam reflected by the curved face was close to the hole: this distance was measured.
The offset of the LC of PR were moved:

θ_X: from 6150 to 5210
θ_Y: from 200 to –930

As far as the translation *a* was concerned, it was necessary to change only the height of the PR mirror. The height of the PR mirror was changed moving the suspension point:

a_y=2 mm (downwards)

2.2.3 North axis with the PR mirror installed and without Brewster link

At this point the HeNe is recollimated, taking into account the PR lens effect, to arrive collimated up to the North End. To do so the third lens of the telescope had to be translated by 10mm closer to the second one. Then the mirrors sending the HeNe beam were moved, first to obtain light at the North End, then to obtain the overlapping of the incident beam with both the beams reflected by the PR. At this point the PR was pretty well perpendicular to the North axis, and the HeNe beam hit the mirror in the center: thus both the PR angle and the center of the mirror were defined. Then a rough measure of the altitude of the beam, with respect to the IB tower flange center, has been performed: the axis found is 1mm lower than the middle of the Injection tower flange. The height of the same laser beam with respect of the levelling reference mark on the floor close to the Signal Recycling tower (marker n.52) resulted about 1.2205 m. Since this reference mark is placed in a small pit, at a depth of about 10 cm, the laser beam (i.e. the interferometer axis) at the level of the PR mirror is about 1.12 m high from the central building floor.

After these operations the PR was supposed to be perpendicular and centered to the North axis as determined by the HeNe direction, with an estimated precision of about 100 μrad and 1 mm.
It has to be observed, however, that after this centering the position of the PR mirror and of the IB has been changed many times. In the further interferometer operations, therefore, the centering on the PR is no more assured. However, the procedure proved to be effective in reaching the centering condition, and can be started again once a precise centering will be required. Moreover, the position of the PR and of the IB was recorded by the local controls CCD, and could in principle be recovered.

2.3. Input Bench positioning: HeNe laser from the laser laboratory

The further step in the prealignment of the whole interferometer consisted in sending a HeNe beam from the Laser Laboratory up to the North End, through all the VIRGO optics present along the North axis. This beam has been installed on the Detector Table (DT) (see Fig. 2.3-1) in the Laser Laboratory, and entered into the interferometer passing through M6 (the last concave mirror of the IB), which had on this beam the effect of a diverging lens. The collimation of the beam had therefore to take into account the presence of the M6 divergent lens and of the PR converging lens (see Appendix 4.2).

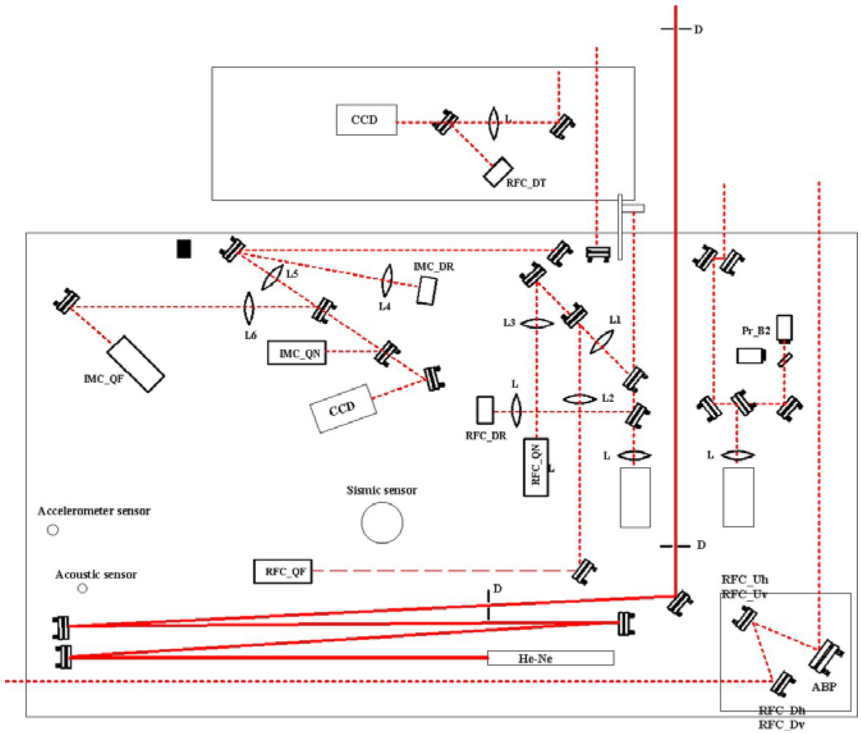

Fig. 2.3-1: *Setup of the detector table with the HeNe for the interferometer prealignment (HeNe: solid line; Nd:YAG: dashed line): the beam is folded in order to obtain a delay line of about 10 m before M6 (on the IB).The two last steering mirror on the HeNe folded path are remotely controllable (mounted on picomotors). Three diaphragms (D) are used as a reference.*

In order to obtain a reasonable beam dimension at the North End the HeNe laser had to be placed quite distant from the PR mirror. Four mirrors have been placed along the optical path of the beam, in order to create a delay line for obtaining an about 10-m-long path until the PR mirror. The expected beam diameter at the NB is about 30 cm. To obtain transmission at 3 km, the HeNe was first autocollimated using the flat face of the PR mirror: since this mirror hasn't been moved after previous prealignment, is was a good geometrical reference. Then the last steering mirror on the Detector Table was tilted until HeNe light was transmitted through the NE. The light transmitted looked like a large red disk, since the beam was larger than the north output window.

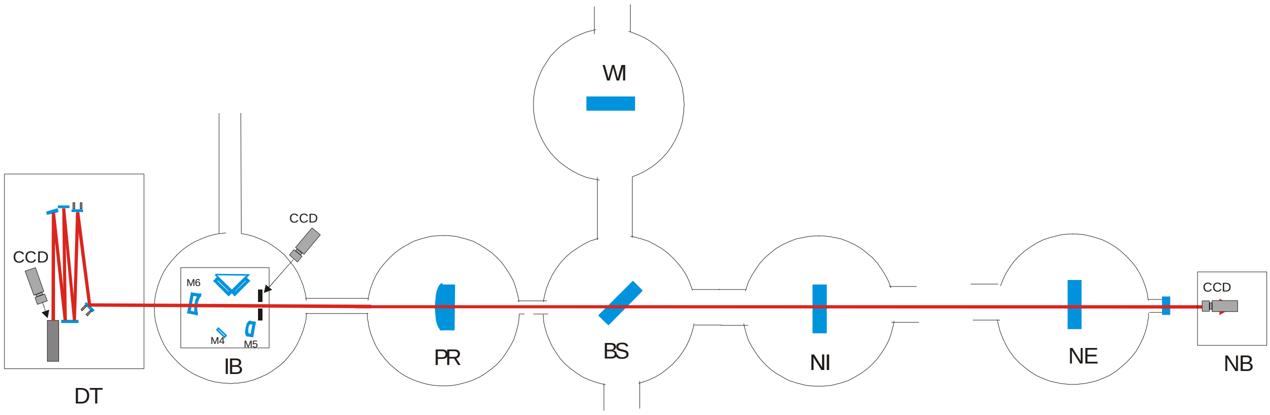

Fig. 2.3-2: *Transmission of the HeNe beam from the Laser Laboratory to the NE bench.*

Once the transmission of the HeNe at the NE is obtained, a first evaluation of the displacement from the center of the PR mirror was obtained looking at the reflection from the curved surface. The PR mirror first kept in the nominal position found in Par.2.2 (i.e. perpendicular to the north axis). Then it was rotated by an angle θ using the LC until the reflection from the curved face was autocollimated with the incident beam (this spot is distinguishable from the reflection from the plane surface because it is larger). The displacement *a* with respect to the center of the PR mirror is equal to $a = R \sin \theta$, where *R*=PR curved face curvature radius (4300 mm). The two spots were observed on the IB output diaphragm (2.5 cm diameter), looking at its north side with a camera (or directly by eye through a port in the tower). The HeNe beam and the IB were repeatedly moved in succession until the two spots (the one from the plane face and that reflected by the curved face) were overlapped (the spot reflected by the plane face passed through the diaphragm and was autocollimated on the HeNe output hole, the one reflected by the curved face was much larger than the diaphragm, and was centered around the diaphragm. In order to obtain at the same time transmission at NE, autocollimation of both reflections by the PR, and centering of the beam in M6 and in the output IB diaphragm, it was necessary to move the IB by 4 mm eastward.

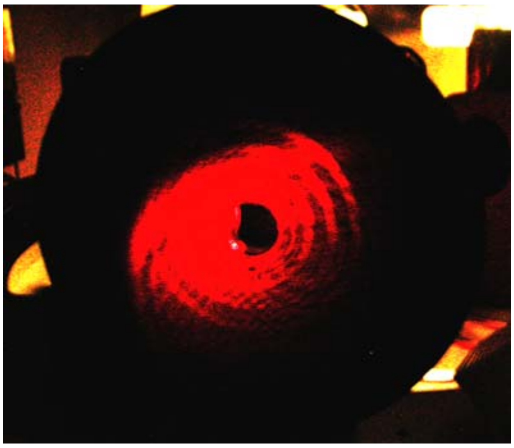

Fig. 2.3-3: *Reflection of the HeNe beam from the curved face of the PR mirror (large spot around the diaphragm): the reflection from the plane face of the PR is passing through the center of the diaphragm.*

In this way the position of the IB with respect to the north axis (as defined in par.2.2.3) was obtained. The precision in this positioning (see 4.3) can be estimated as being about 0.5 mm (sensitivity of the autocollimation of the PR plane face reflection on the HeNe laser output to the IB movement).

2.4. Input beam alignment

2.4.1 Nd:YAG dirty beam

In the following step use was made of the Nd:YAG beam. At that stage the IMC was not locked yet, therefore it was not possible to use the final Virgo beam. A portion of the Nd:YAG beam was then picked off before entering in the IB tower. It was sent to the IMC output mirror of the dihedron, reflected to M4, M5 and M6, thus along the same path of the final Virgo beam transmitted by the IMC. This beam, also called "dirty beam", was overlapped as much as possible on the HeNe beam in the Laser Laboratory by autocollimating the reflection from the plane face of the PR on the output of the HeNe. The beam was then aligned along the North axis moving M5 and M6 until transmission at the NE was obtained. As a monitor, during this alignment, either the reflection by the PR on the MC mirror and the spot, reflected back by the PR and then transmitted by M6 at the output of the HeNe, were used. The light was detected by a CCD camera placed on the NB. The big 1-m focal lens (L1, 23-cm diameter) at the output of the North tower was installed, and the CCD was placed close to the focus of that lens, without any objective.
The use of the dirty beam allowed to understand how to steer M5 and M6 in order to obtain transmission at the NE, and what to look at for doing this. The CCD imaged the ring of the L1 lens with the transmitted beam spot within it. The centering of the beam at the North End was performed by steering the mirror with the M6 mirror, taking the L1 holder as a reference.

2.4.2 Nd:YAG after MC locking: transmission at NE and NI prealignment

After the locking of the IMC transmission of the Virgo beam at the North End was obtained quite easily, acting in a similar way as in the case of the dirty beam. Even in this case the reflection by the PR mirror on the MC mirror was taken as a reference, and the M5 and M6 mirrors were moved until transmission at the NE was obtained.

2.5. North Fabry-Perot alignment

2.5.1 NI prealignment

The HeNe beam was first used to prealign the NI mirror, looking at the light reflected through the PR into the Laser Laboratory (the HeNe beam spot reflected by the NI mirror was autocollimated at the output of the HeNe laser itself). This operation required the use of the marionette motors. The NI mirror was moved by about 3 mrad in θ_x (upward, i.e. the reflection by the NI toward the IB moved upward) and by about 4.5 mrad in θ_y. The finer alignment of the NI mirror was obtained looking at the Nd:YAG light reflected back by it to the output of the HeNe laser (the spot was faint but still visible by the digital CCD camera looking at the HeNe laser output).

2.5.2 North Arm alignment: fringes at NE

The NE mirror was aligned using an autocollimator (see Par.4.3). The autocollimator was mounted on the NB, at about 2 m apart from the NE mirror (Fig. 2.5-2). The big 1-m focal length lens was removed. The autocollimator was first aligned using the HeNe beam. At the NE the

HeNe transmitted beam was almost a plane wave: its light was focused on the autocollimator focal plane as a small spot. The autocollimator was illuminated by the HeNe light, and then oriented until that small spot was centered on the reference cross of the autocollimator. Then the HeNe was switched off, and the light source of the autocollimator was switched on. An additional visible laser diode had been previously used to understood roughly which was the orientation of the NE mirror with respect to the North axis (Fig. 2.5-1): a BS had been placed in front of the autocollimator, reflecting toward the NE mirror part of the light of said additional laser. The laser was aligned on the NE mirror in order to get the light reflected by the NE and the BS on the laser output. Then the light reflected by the NE mirror and transmitted by the BS was observed: in this way a rough idea of the orientation of the NE mirror with respect to the autocollimator (i.e. of the North axis) was available.

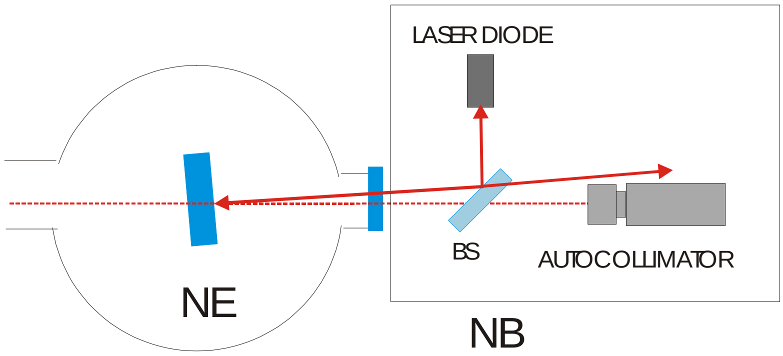

Fig. 2.5-1: *Set-up of the autocollimator and a diode laser for checking the initial position of the NE mirror: the autocollimator is aligned along the HeNe coming from the laser laboratory; moving the beam splitter BS the beam from the laser diode is made perpendicular to the NE (autocollimated on the laser diode); the light coming from the laser diode is impinging perpendicular on the NE. The light transmitted back to the autocollimator through the BS gives a rough hint about the initial NE orientation.*

Using the autocollimator the NE mirror could be aligned using the marionette motors. The first operation was to obtain the crosses reflected by the NE mirror visible by the autocollimator CCD: the two visible crosses correspond to the reflections by the two surfaces of the NE mirror: the wedge of the NE being below, the cross reflected by the “right” face (the southern, that is the curved) should appear above the other (when the autocollimator CCD was properly oriented). Moreover, it turned out that the intensity of the cross reflected by this face, even if it was the second face to be illuminated by the light of the autocollimator, appeared as the more intense on the autocollimator CCD. In order to obtain the overlapping of this cross with the reference cross of the autocollimator (and with the spot of the HeNe), the NE mirror was moved by about 10 mrad in the forward direction, i.e. the perpendicular to the reflective surface of the NE mirror was inclined downwards). The marionetta θ_x balance motor was used, but the displacement was so large that the beam used for the local controls went out of the PSD. A repositioning of the PSD was necessary. A movement of about a couple of mrad in θ_y was necessary. The global precision of all this centering and aligning operations is estimated to be of the order of 100 μrad (reproducibility of the autocollimator positioning).

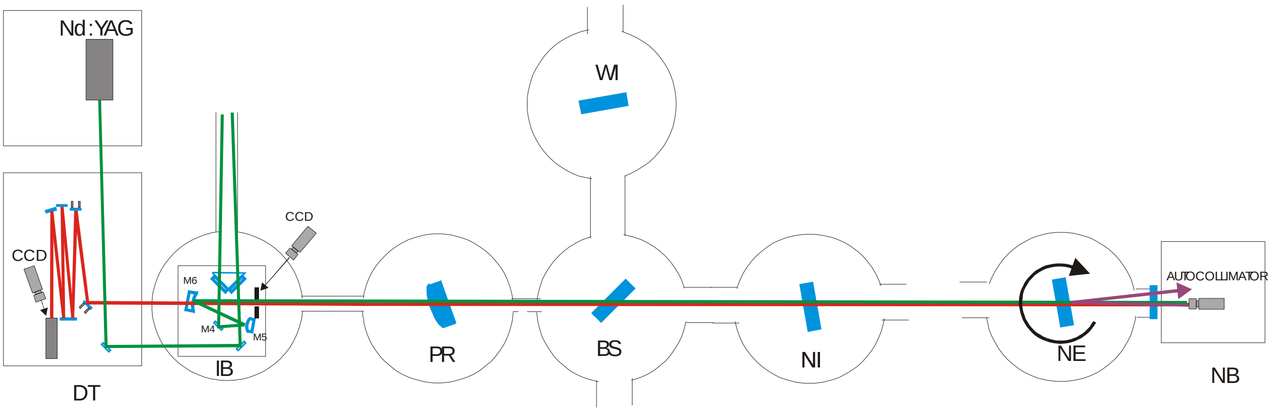

Fig. 2.5-2: *Alignment of the NE mirror using the HeNe beam and the autocollimator on the NE bench.*

To align the North Cavity, i.e. to look for flashes and transmitted Airy fringes, a CCD camera was placed (using a 5% BS) on the NB at about the image plane of L1, using, in addition to the 1-m focal length lens L1 and a –200 m focal lens (L2) (according to the external benches design), a further 50 mm focal lens. This camera made the image of the L1 edge together with the light spots produced by the impinging Nd:YAG and its multiple reflections inside the cavity. These spots were centered inside the NE acting on the M6 mirror.
As a first step the NI mirror alignment (obtained previously with the HeNe) was checked again using the Nd:YAG beam, autocollimating the light reflected by the NI on the output of the NeNe laser (this spot is very faint but visible with the digital CCD).
The further operation consisted in moving the NE mirror around the position found with the autocollimator. After some steps around this position the first small flashes became visible. Further movements of the NI and NE mirror by about 10 μrad yielded more intense flashes, and then the cavity modes could be indentified. The two mirrors were moved finely, at steps of about 1 μrad, in order to get an intense TEM_{00} mode. The finer alignment of the cavity was obtained once the PR_B7 photodiode was aligned, and the transmitted Airy peaks were detected, by maximising the peaks of the fundamental modes and minimising the peaks of the higher modes.

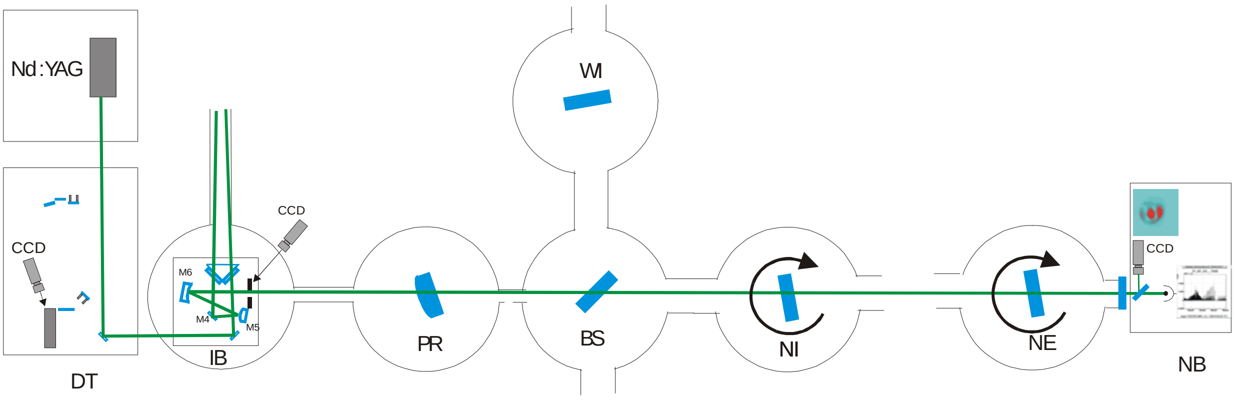

Fig. 2.5-3: *Alignment of the North cavity, until the resonant gaussian modes are visible.*

2.5.3 BS prealignment: light at WE

The goal of this task was to align the BS mirror in its correct position, in order to send a light beam, which is properly aligned along the North axis, up to the West End.
After having aligned the Nd:YAG beam along the North axis, the BS mirror was moved in order to get transmission at the West End. As a first step, the BS was moved until the Nd:YAG beam reflected by the NI was visible by the cameras of the detection system: the BS marionetta balance motor θx was moved by about 45,000 steps forward. The NI mirror was also slightly realigned, in order to get interference between the PR and NI reflected beams at the DB level.
Then the HeNe beam was used: it was first checked that the beam was passing centered through the WI mirror. The 1-m focal lens at the WE was removed. A screen was placed on the West External Bench, with a CCD camera (cam8p) looking at it. The BS was moved until light transmission at the WE was obtained. The new position was close to that found by aligning it on the DB (less than 100 μrad).
The 1-m focal length lens (L1) at the WE was put back in place. A CCD digital camera, without objective, was placed on the West External Bench close to the focus of the 1m-f lens. This camera could see the holder of the 1-m focal length lens edge. It was checked that the HeNe spot was still visible. The HeNe was then switched off. The light of the Nd:YAG was already partly transmitted and visible. A further fine alignment of the BS (a few tens of μrad) was now necessary to center the Nd:YAG inside the 1-m focal length lens holder as visualised by the CCD.

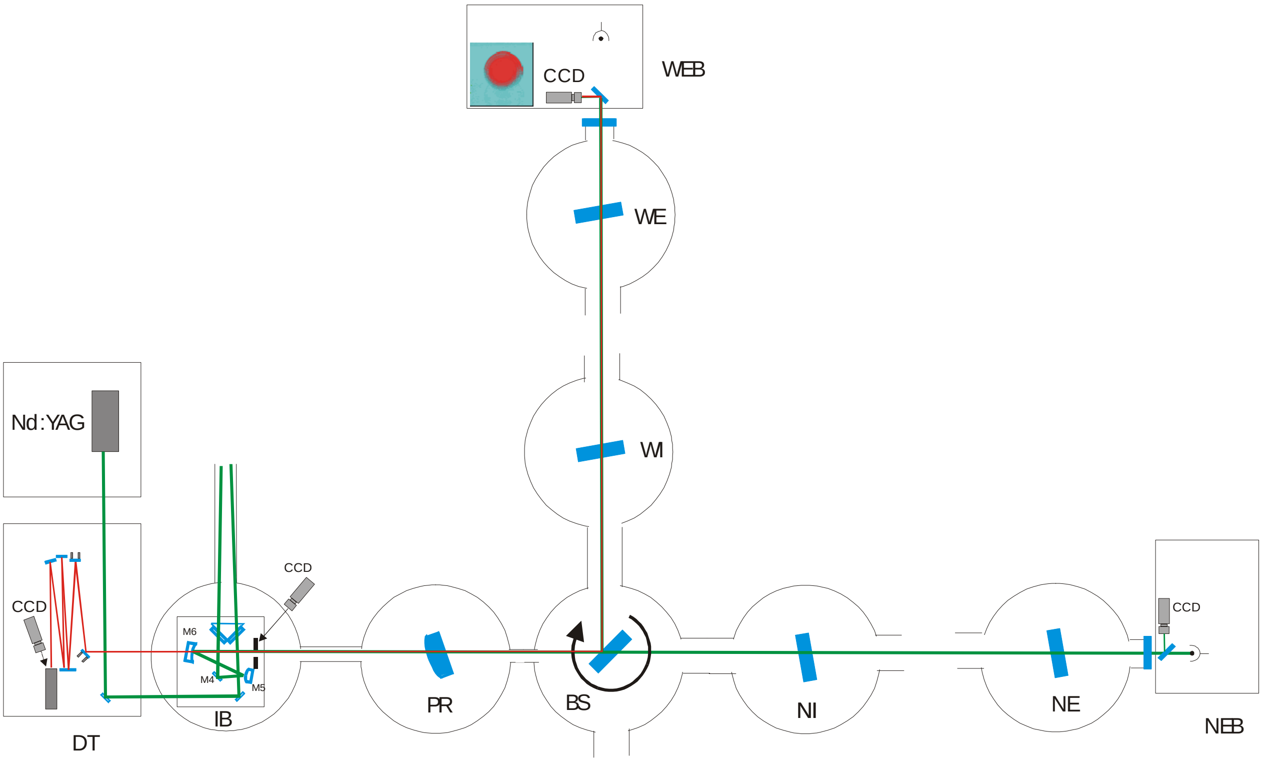

Fig. 2.5-4 *Alignment of the BS: HeNe and Nd:YAG light visible at the WE.*

2.5.4 DB and North External Bench alignment

Once the North Arm and the Beam Splitter had been aligned, the detection bench was aligned in the following way: the bench was placed on its support with a position close enough to its reference position. Since the beam was more than 1 cm lower than the center of the first lens (L1), the 13 mm spacers below L1 and M1 have been removed (these spacers were used during the CITF). The beam was then found to be well centered on L1 and M1 within about 2 mm. Then the beam was centered on M2 using M1 orientation. M2 was moved in order to center the beam B1 on the L3 lens. The matching of B1 on the Output Mode Cleaner (OMC) was performed using M5 and M6 mirrors. Once B1 was well enough aligned on the OMC, the beam B5 has been centered on the quadrant photodiodes (DQ1 and DQ2) using M3 and M4 mirrors.

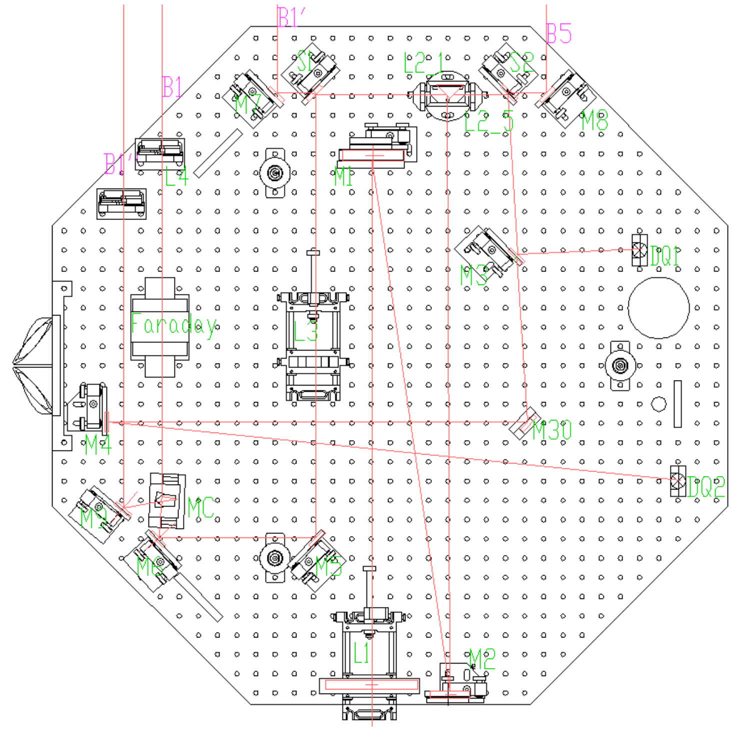

Fig. 2.5-5: *Optical layout of the suspended Detection Bench (DB).*

The bench was then suspended in air and put in its reference position (using the local controls). On the External Bench, the beams were centered on the photodiodes and cameras. A fine alignment of B1 on the OMC was done and gave a transmission of about 75-80% (TEM_{00}). The beam waist was not adjusted on the OMC waist since the input beam did not yet have the correct size (to be done by translating L1 and L3).

The detection tower was then put under vacuum. The bench was moved (using the local controls) and the telescope (M1 and M2) realigned until the beams position on the external bench cameras were the same as before (i.e. with tower in air).

To align the North External Bench, the B7 photodiode has first been roughly centered using the HeNe beam. When the north cavity was aligned the B7 photodiode centering has been tuned.

Once the North End Bench telescope was aligned the photodiodes and camera have been moved (and realigned) in order to be positioned at the beam waist. Two mirrors have also been added in order to make easier the alignment of the beam on the photodiodes and camera.

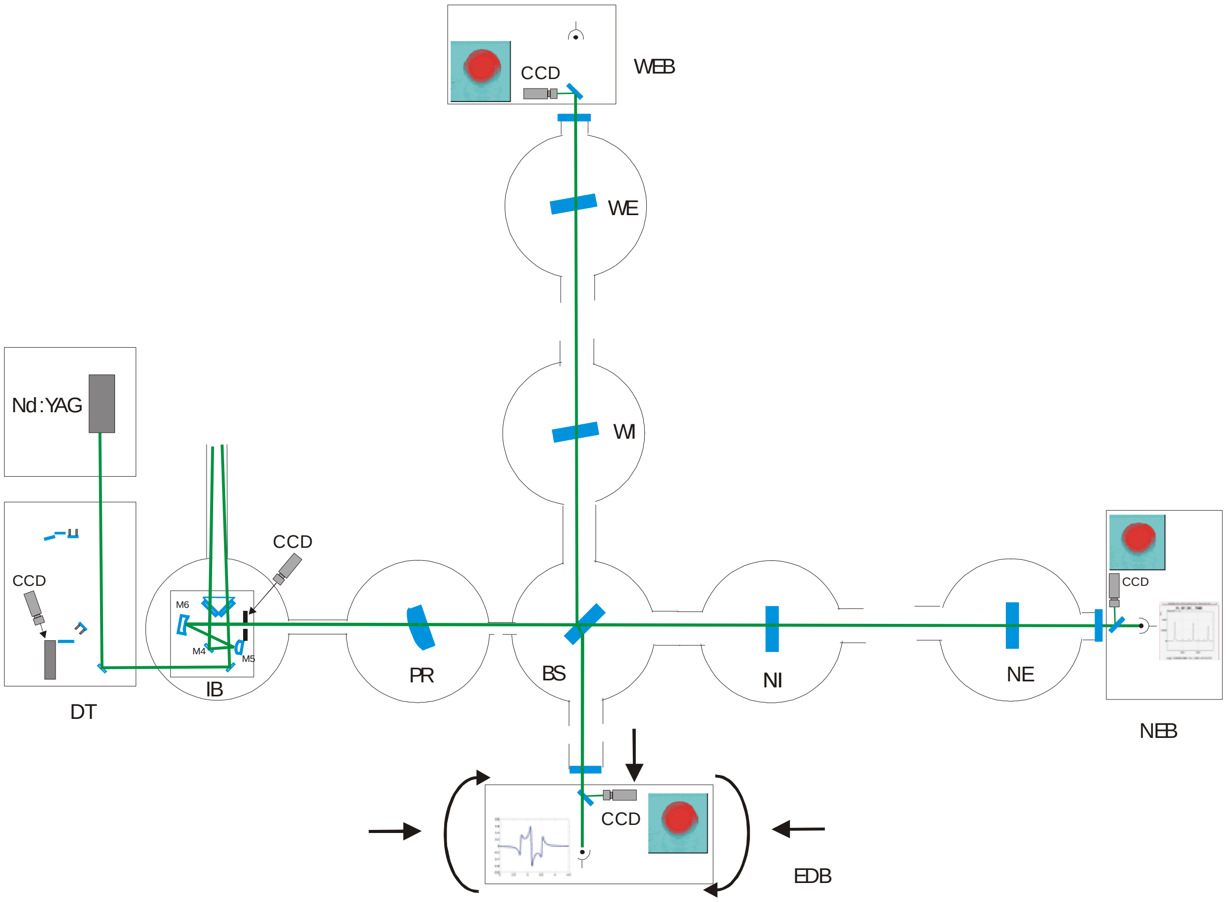

Fig. 2.5-6: *Alignment of the DB: the light reflected by the aligned North cavity is centered on the DB photodiodes and cameras, by moving the DB suspension.*

2.6. West Fabry-Perot alignment

2.6.1 WI prealignment: light on the DB

To prealign the WI mirror the following procedure was followed:
First the HeNe beam was used in order to understand whether the WI mirror was roughly aligned perpendicularly to the West axis moving the motors and the ty coarse: the WI was moved until the HeNe was reflected back to the Laser Laboratory. The main movement was in the θ_y direction, in which the mirror was moved by 6.4 mrad (on the PR the beam coming from the WI, reflected by the BS, moved toward west), whereas in the θ_x direction the motors were moved by 4.3 mrad (70,000 steps) (on the PR the beam coming from the WI, reflected by the BS, moved upward). The PSD went out of range and their recentering was necessary.
The Nd:YAG beam was then autocollimated on the DB (B1p camera) moving the Local Controls of θ_x and θ_y .
The fine alignment was obtained by maximizing the Michelson fringes made by the WI and the NI on the Pr_B1p_DC photodiode, once the NI was aligned using the PR-NI and North cavities.

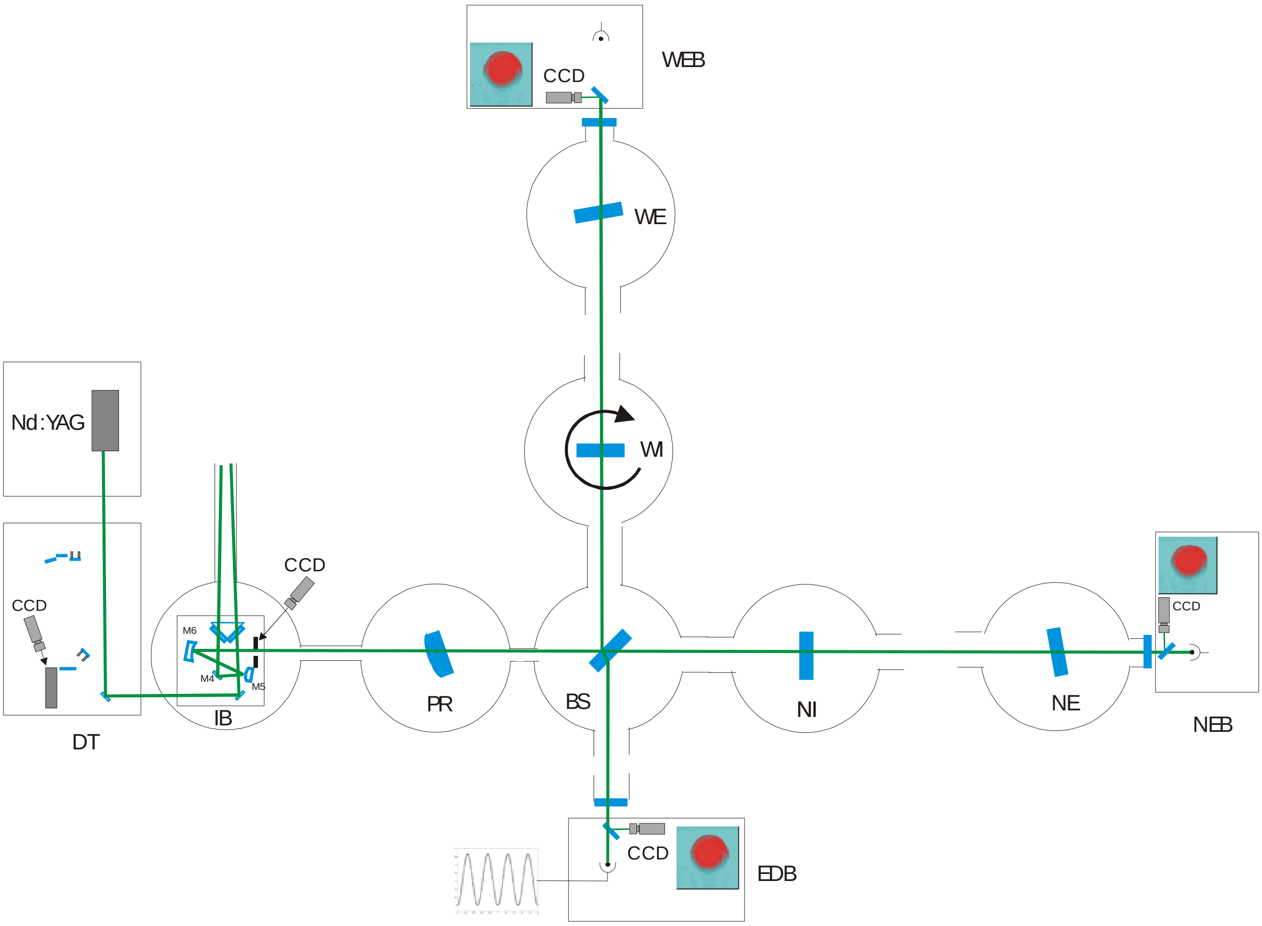

Fig. 2.6-1: *WI alignment: the light reflected by the WI is made visible on the DB and the NI-WI Michelson fringes are maximized.*

2.6.2 West Arm alignment: fringes at WE

The alignment of the West End mirror has been carried out analogously to the North End one (see Par.2.5.2).
In order to obtain the overlapping of the cross reflected by the WE mirror with the reference cross of the autocollimator (and with the spot of the HeNe), the WE mirror was moved by about 2.9 mrad in the backward direction (i.e. the perpendicular to the reflective surface of the WE mirror was moved upward on the West Bench). The marionetta θ_Y balance motor was used to displace by 16 mrad (on the West Bench the spot reflected by the WE mirror moved eastward). A repositioning of the PSD was necessary. As for the NE, the precision of all this centering and aligning operations is of the order of 100 μrad (repeatibility of the measurement).

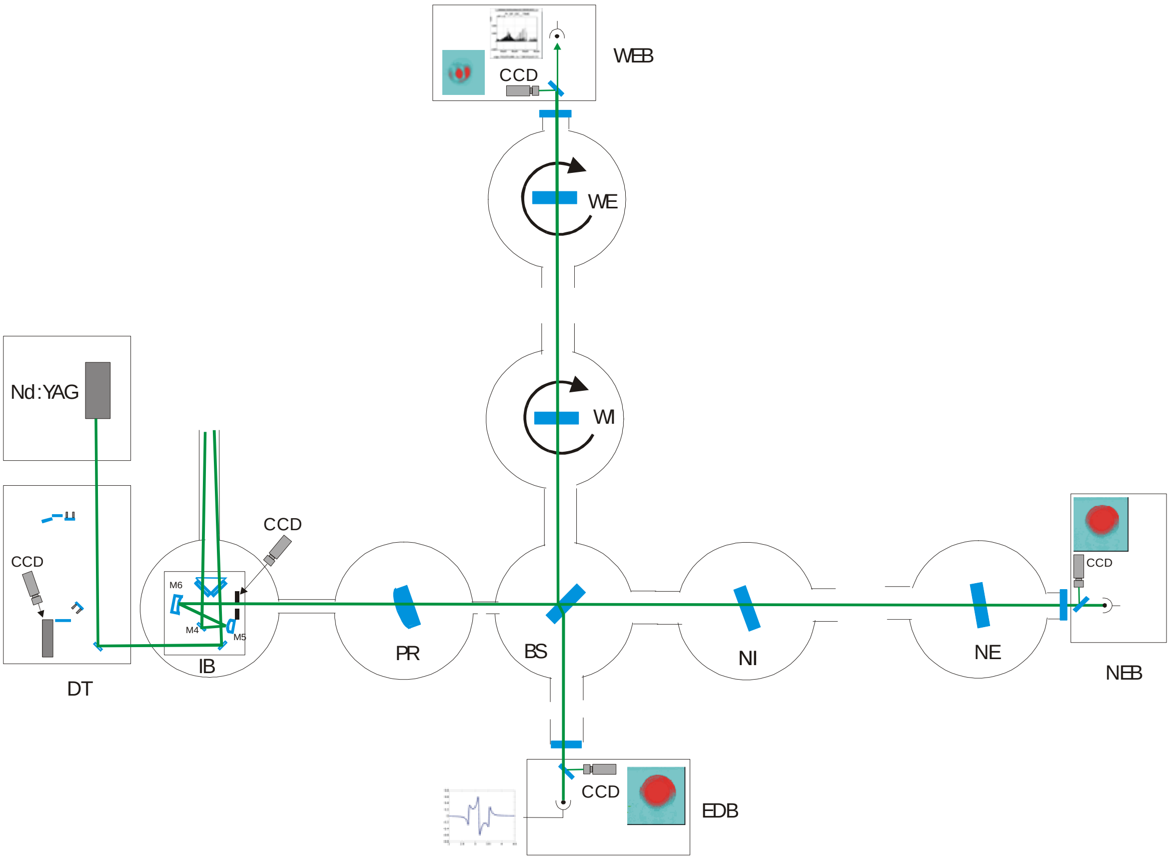

Fig. 2.6-2: *West cavity alignment: after having aligned the WE with the autocollimator, the WI and the WE are moved until the gaussian modes are resonating.*

As for the NE, to align the West Cavity, the flashes and transmitted Airy fringes by the West Cavity were visualized by a CCD camera placed (using a 5% BS) on the WB at about the image plane of the WE mirror, using, also in this case, in addition to the 1-m focal length lens L1 and to the L2 divergent lens, a further 50 mm focal lens. The imaged edge of the L1 mirror was taken as a reference for centering the Nd:YAG beam on the WE mirror.

As a first step the WI mirror was aligned using the Nd:YAG beam reflected to the DB. As a reference position the overlapping with the aligned NI reflection to the DB was taken. The further operation consisted in moving the WE mirror around the position found with the autocollimator. To find the first flashes at the WE many movements, globally within 100 µrad, were necessary. This phase was quite long, essentially proceeding by trials and errors. After the first flashes were visible, further movements, within 10 µrad, of the WI and WE mirror made the cavity modes recognizable. The two mirrors were moved finely, at steps of about 1 µrad, in order to get an intense TEM_{00} mode. The finer alignment of the cavity was obtained once the PR_B8 photodiode was aligned, and the transmitted Airy peaks were detected, by moving the mirrors by a few microradiants to maximize the peaks of the fundamental modes and minimize the peaks of the higher modes.

3. Conclusion

Globally, the movements of the mirrors to obtain the prealignment conditions were the following:

PR: 2mm vertical (downwards); θ_X: 940 µrad; θ_Y: 1.13 mrad.

IB: 4 mm eastward.

NI: θ_X : 3 mrad; θ_Y :4.5 mrad.

NE: θ_X: 10 mrad; θ_Y : 2 mrad.

BS: θx: 2.8 mrad; θ_Y : < 100 μrad.

WI: θ_X : 4.3 mrad; θ_Y : 6.4 mrad.

WE: θ_X : 2.9 mrad; θ_Y : 16 mrad..

4. Appendix

4.1. Computation of the off centering of the input beam on the PR mirror

In the following the geometry and parameters used in the computation of the angles and offset of the PR position with the incident HeNe beam are shown.

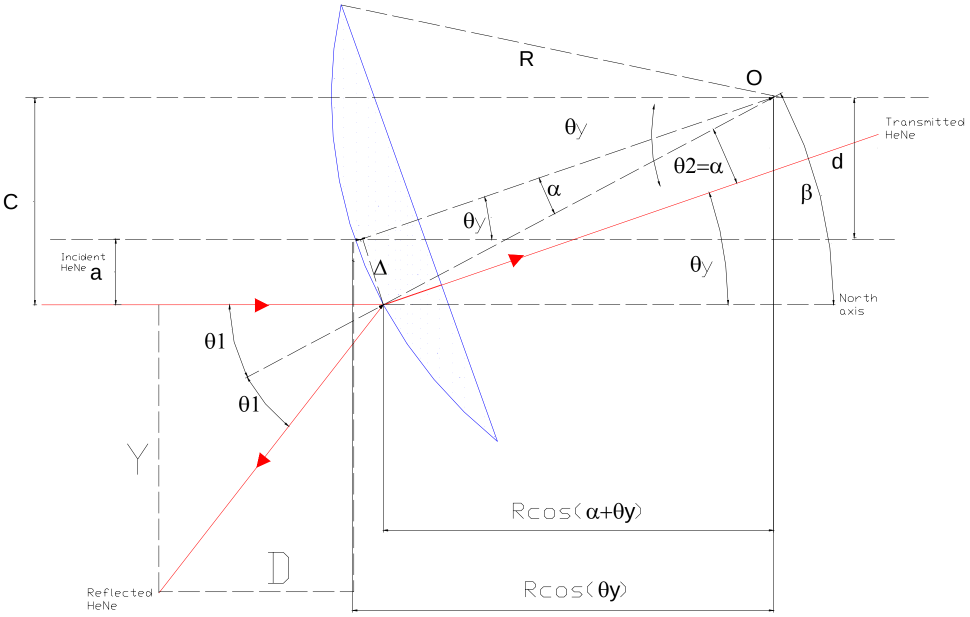

Fig. 4.1-1: *Geometry and parameter for centering the input beam on the PR mirror.*

$$\alpha = \arcsin\left(\frac{1}{n}\sin\theta_1\right)$$

$$\alpha = \arccos\frac{\Delta}{R}$$

$$\beta = \theta_1 = \theta_Y + \alpha$$

$$a = \Delta\cos\theta_Y$$

$$a = R\sin(\theta_Y + \alpha) + R\sin\theta_Y$$

$$\theta_2 = arcsen\left[\frac{1}{n}\sin\theta_1\right] = arcsen[\sin(\theta_Y + \alpha)]$$

$$\theta_1 = \frac{1}{2}\arctan\left(\frac{Y}{D}\right) = \theta_Y + \alpha \qquad \Rightarrow \qquad \alpha = \frac{1}{2}\arctan\left(\frac{Y}{D}\right) - \theta_Y$$

$$\theta_2 = \alpha = \arcsin\left[\frac{1}{n}\sin(\theta_Y + \alpha)\right]$$

$$\Downarrow$$

$$\begin{cases} \alpha = \frac{1}{2}\arctan\left(\frac{Y}{D}\right) - \theta_Y \\ \alpha = \arcsin\left[\frac{1}{n}\sin\theta_1\right] \end{cases}$$

$$\Downarrow$$

$$\begin{cases} \theta_Y = \theta_1 - \arcsin\left[\frac{1}{n}\theta_1\right] \\ a = R\sin(\theta_Y + \alpha) + R\sin\theta \end{cases}$$

The various elements are plotted with two different R (4100 and 4500 mm) (Fig. 4.1-2:):

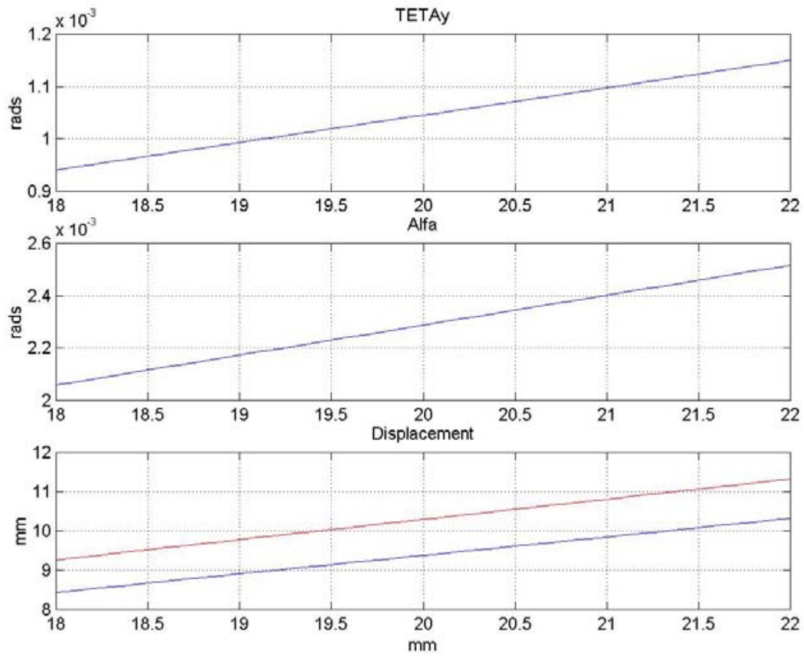

Fig. 4.1-2:

4.2. HeNe collimation from the Laser Laboratory to the North End

The parameter and computations involved in the collimation of the HeNe beam from the Laser Laboratory to the North End are the following: M6 is the mirror of the Injection bench that sends the beam in the interferometer and which is hence on the North axis. It is 10 mm thick, with a refraction index of (silica) of 1.457 for HeNe. Its southern face is plane, and the northern face has a curvature of –3160 mm (it is a concave mirror for the beam going into the interferometer). For a HeNe passing through it, it is therefore a divergent lens having *f*=-6914 mm. It is distant by 5300 mm from PR mirror (-4300 mm curvature and 30 mm thickness). The PR mirror is 3km far from the end mirror NE, which has 3630 mm curvature and 96 mm thickness.
The following plots show the size (upper plot) and position (lower plot) of the beam as a function of the distance from the waist to the M6 mirror, just after the recycling mirror. All units are mm.

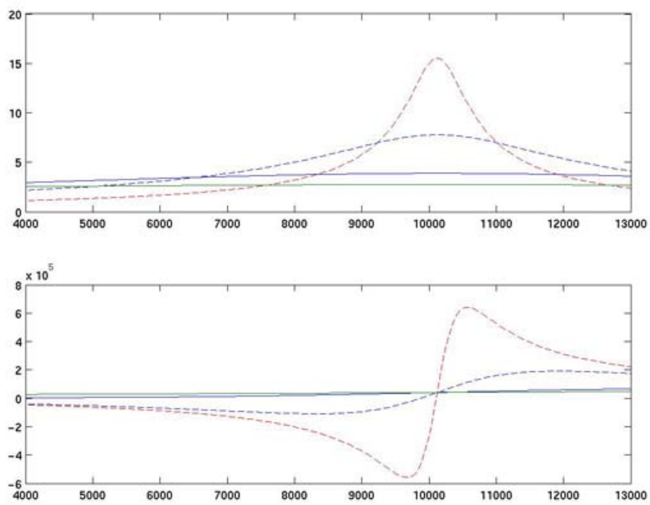

Fig. 4.2-1: *Size (upper plot) and position (lower plot) of the beam as a function of the distance from the waist to the M6 mirror, just after the recycling mirror. All units are mm. Red dashed line :*w_0*=0.3mm; Blue dashed line:* w_0*=0.6mm; Blue solid line:* w_0*=1.2mm; Green line:* w_0*=1.7mm.*

1 m after the NE mirror the size of the beam is:

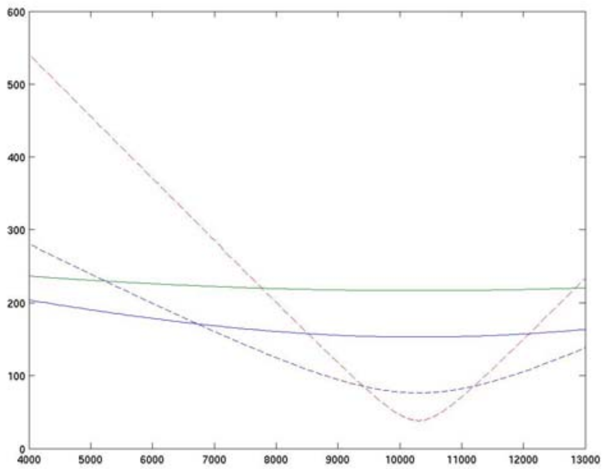

Fig. 4.2-2: *Size of the beam one meter after the NE mirror(units in mm)*

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4.3. Vertical displacement of the IB

The effect of a displacement (vertical or lateral) of the IB on the spot which, coming from the HeNe and passing through M6, is reflected back to the HeNe itself by the plane face of the PR, is computed using the ABCD matrix propagation. The lateral displacement of M6 with respect of the other parts of the optical system (HeNe laser and PR), which are considered to be aligned, has to be taken into account. In order to do so, first the propagation of the beam from the HeNe to the M6 mirror is considered, with the beam translated with respect to the M6 lens by the opposite of the IB displacement, i.e. the displacement of M6 is simulated by displacing the input beam in the opposite direction with respect to the center of the lens. After M6, the output vector is translated back again, in order to come back to the HeNe-PR reference axis. This procedure is applied again when the beam is coming back from the PR to the M6 lens. The various steps are written as follows:

$$\begin{pmatrix} x^{OUT}{}_{M6} \\ \alpha^{OUT}{}_{M6} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f_{M6} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_{HeNeM6} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} -x_{IB} \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} x^{IN}{}_{PR} \\ \alpha^{IN}{}_{PR} \end{pmatrix} = \begin{pmatrix} x^{OUT}{}_{M6} \\ \alpha^{OUT}{}_{M6} \end{pmatrix} + \begin{pmatrix} x_{IB} \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} x_{PR-M6} \\ \alpha_{PR-M6} \end{pmatrix} = \begin{pmatrix} 1 & d_{M6PR} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{PR} & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{PR} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_{M6PR} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x^{OUT}{}_{M6} \\ \alpha^{OUT}{}_{M6} \end{pmatrix}$$

$$\begin{pmatrix} x^{IN}{}_{PR-M6} \\ \alpha^{IN}{}_{PR-M6} \end{pmatrix} = \begin{pmatrix} x_{PR-M6} \\ \alpha_{PR-M6} \end{pmatrix} - \begin{pmatrix} x_{IB} \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} x^{OUT}{}_{PR-M6} \\ \alpha^{OUT}{}_{PR-M6} \end{pmatrix} = \begin{pmatrix} x^{IN}{}_{PR-M6} \\ \alpha^{IN}{}_{PR-M6} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{M6} & 1 \end{pmatrix}$$

$$\begin{pmatrix} x_{M6-HeNe} \\ \alpha_{M6-HeNe} \end{pmatrix} = \begin{pmatrix} 1 & d_{HeNeM6} \\ 0 & 1 \end{pmatrix} \left[\begin{pmatrix} x^{OUT}{}_{PR-M6} \\ \alpha^{OUT}{}_{PR-M6} \end{pmatrix} + \begin{pmatrix} x_{IB} \\ 0 \end{pmatrix} \right]$$

The global propagation gives:

$$\begin{pmatrix} x_{HeNe\_back} \\ \alpha_{HeNe\_back} \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & d_{HM6} \\ 0 & 1 \end{pmatrix} \left\{ + \begin{pmatrix} x_{IB} \\ 0 \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ -1/f_{M6} & 1 \end{pmatrix} \left\{ - \begin{pmatrix} x_{IB} \\ 0 \end{pmatrix} + \begin{pmatrix} 1 & d_{M6PR} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{PR} & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{PR} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_{M6PR} \\ 0 & 1 \end{pmatrix} \left[\begin{pmatrix} 1 & 0 \\ -1/f_{M6} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_{HM6} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} -x_{IB} \\ 0 \end{pmatrix} + \begin{pmatrix} x_{IB} \\ 0 \end{pmatrix} \right] \right\} \right\}$$

in which x_{IB} is the IB displacement, f_{M6} is the focal length of M6 (-7022 mm), f_{PR} is the focal length of the PR (9555 mm), d_{M6PR} is the distance between M6 and the PR (5300 mm), d_{HM6} is the distance between the HeNe laser and M6 (11000 mm).
In the following graph the sensitivity of the spot on the HeNe output in dependence on the IB displacement is shown: an amplification of a factor 3 is present.

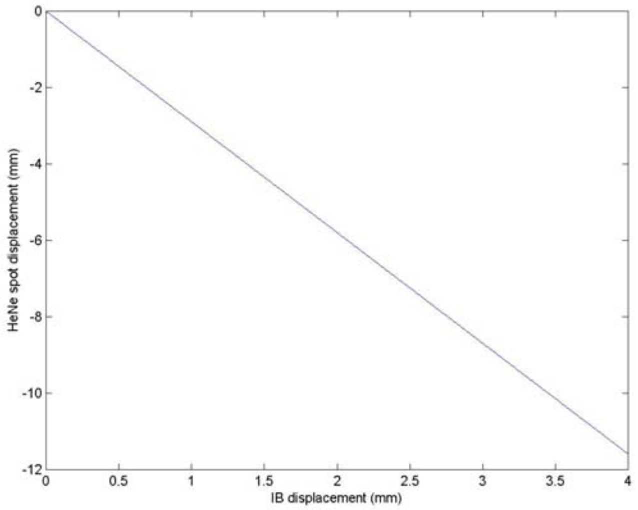

Fig. 4.3-1: *Displacement of the spot, reflected back by the plane face of the PR, on the output of the HeNe, in dependence of a translational displacement of the IB. For one mm of displacement of the IB a displacement of the spot on the HeNe laser is present.*

On the HeNe output a precision better than one mm is detectable, which implies a precision of at least 500 μm on the IB positioning.

4.4. The Autocollimator

The autocollimator was a Möller-Wedel mod. AKRV 300/65/14.7 ME 229707, with an objective focal length of 300 mm, an adjustable tube length (±25 mm) and a precision of about 15 μrad.. The autocollimator principle of functioning consists in projecting the image of a grating (a cross shaped slit) in a parallel beam of collimated light on a reflective plane surface, which retroreflects back inside the autocollimator eyepiece. In the eyepiece an analogous grating (a cross) is present on the object plane of the objective. The instrument is tuned so that when the reflective surface is perpendicular to the autocollimator axis the cross reflected back by the reflecting surface is exactly superimposed to the eyepiece grating (see Fig. 4.4-1). The two gratings are imaged by a CCD camera on a monitor.

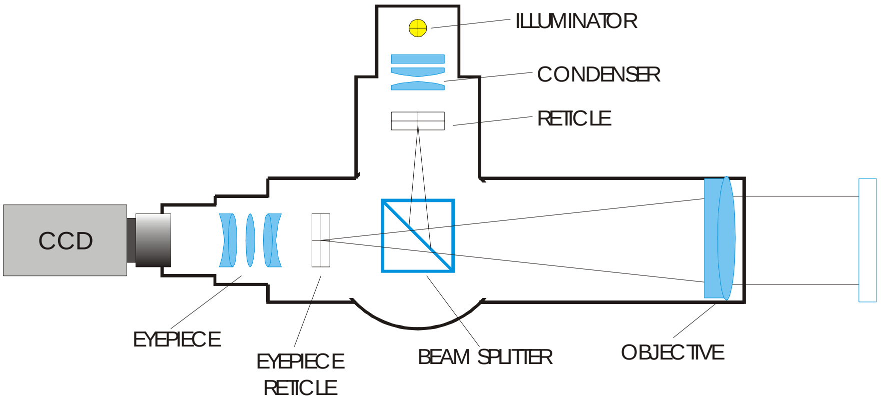

Fig. 4.4-1

In a similar way, the autocollimator can be used taking an incident beam as a reference. In the case of the alignment of the 3-km cavities the HeNe transmitted from the Laser Laboratory to the terminal buildings arrives at the end mirrors with a diameter of about 30 cm. Therefore, it can be considered with a good approximation as a plane wave. The autocollimator illuminator is switched off. Its objective focalizes the HeNe beam onto the eyepiece grating, so that the autocollimator itself can be aligned along this beam until the focalized spot of the HeNe beam is on the center of the eyepiece grating: this condition corresponds to having the autocollimator parallel to the HeNe beam. At this point the HeNe can be switched off, and the illuminator on. The grating is projected onto the suspended mirror and reflected back into the eyepiece. The suspended mirror can then be moved until the autocollimation condition is satisfied. This means that the suspended mirror is now perpendicular to the autocollimator, this latter being parallel to the HeNe beam, i.e. to the 3-km axis.

5. References

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Ref. 2: VIR-SPE-DIR-1300-114, "Interferometer Geometry Central ITF Items position"

Ref. 3: VIR-SPE-LAS-1300-115 (Issue 5: Draft), "Geometry Reference System".

Ref. 4: VIR-SPE-DIR-1300-128, "VIRGO Geometry Tunnels and tubes".

Ref. 5: VIR-NOT-CAS-1390-210, "Beam Deviation Due to De-centering of Power Recycling Mirror Curved Surface".