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The VIRGO-1998 Detection Bench Telescope

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V. Sannibale
(*sanni@lapp.in2p3.fr*)

Laboratoire d'Annecy-le-Vieux de Physique des Particules
Chemin de Bellevue BP 110, 74941 Annecy-le-Vieux CEDEX, FRANCE

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Project Office: INFN-Sezione di Pisa * Via Livornese, 1291-56010 San Piero a Grado, Pisa Italia.
Secretariat: Telephone (39) 50 880 327 or 880 352 * FAX (39) 50 880 350 * e-mail virgo@pisa.infn.it

1 Introduction

The main characteristic of the VIRGO98 detection bench telescope and his final optical elements specifications are presented.

The optical characteristics and the allowed errors on the focal lengths are discussed also, except the surface roughness which has beens evaluated in a previous note [1].

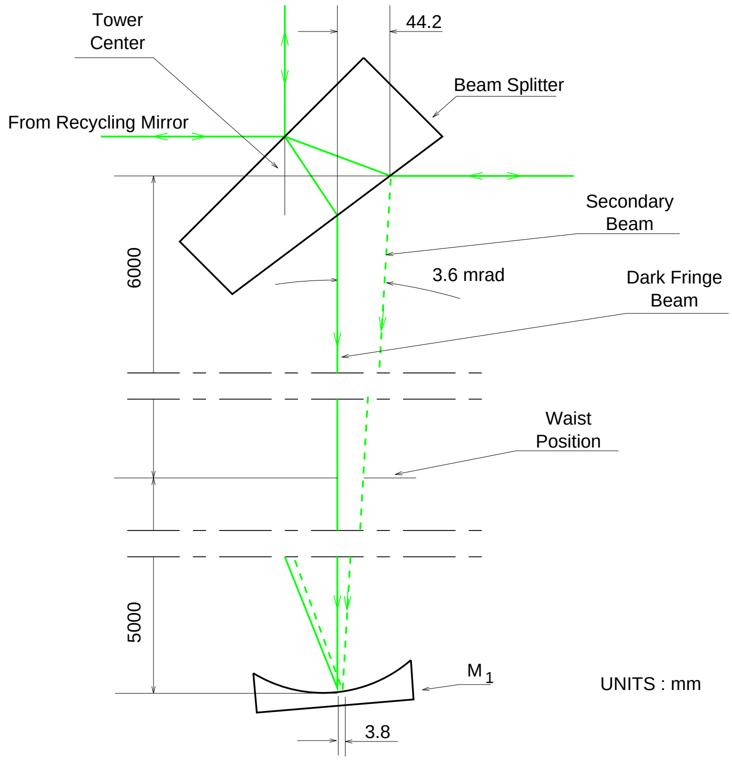

Figure 1: Beam Splitter geometry.The drawing is not in scale, to simplify the quotes reading.

2 Device Functions

The detection bench telescope has to fulfill the following main functions

- Separation of the dark fringe beam from the beam reflected by the second beam splitter face, (see fig. 1 and fig. 2).
- Beam size reduction for the matching of the mode cleaner waist and
- Beam size fitting into the active area of the photodiodes, used to detect the interferometer signals.

The necessity to separate the two beams is due to the fact that they intersect on to the detection bench with a little angle (3.6 $mrad$) and their distance on the table is roughly equal to their spot size [3].

The principle to achieve the beam separation, is simply to reduce the spot of the beams and to use a focusing optical system (at least a single lens) which transform the converging rays into the diverging rays.

The first two spherical mirrors of the detection bench telescope make the beams separation and reduce the beam size to $w \simeq 1\ mm$, with a far field divergence $\theta_\infty \simeq 0.3\ mrad$. A prism after the two mirrors is placed to separate the two beams.

A third lens is needed to reach a waist of 140 μm for the right matching of the mode cleaner cavity.

The beam size of $\simeq 1\ mm$ and the far field divergence chosen are a good compromise for the following reasons

- the standard commercial mounts and optical devices of 1 inch diameter can be used.
- the beam can be propagated enough far without need to be refocused.
- Easy way to reduce the beam waist (with a lens) to match the mode cleaner cavity.

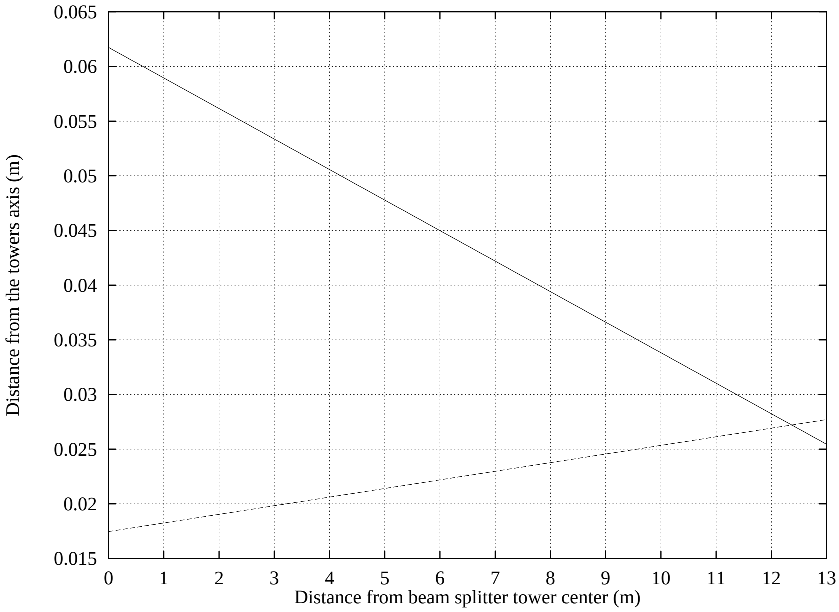

Figure 2: Distance of the two beams from the tower axis. The continuous line is the secondary beam and the dotted one is the dark fringe beam. The distance is measured from the beam splitter tower center. The detection tower center is located at 11 m.

3 Device Constraints

In order to minimize the TEM_{00} power losses due to optical elements used in the detection bench telescope, the following specifications has been fixed:

- Minimum number of optical components as possible.
- Losses due to the diffusion and absorption for each element $\sim 10^{-4}$.
- Spherical aberrations which produces TEM_{00} losses $\sim 10^{-4}$ [4].
- Beam astigmatism which gives TEM_{00} losses $\sim 10^{-4}$.

Besides that, the telescope has to fit as possible in the VIRGO-2000 detection bench configuration.

4 Telescope Geometry

The propagation of a beam trough an optical system in the paraxial approximation, is completely defined by the ABCD matrix [2]

$$\hat{M} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \tag{1}$$

whose elements depends on the system geometry.

To calculate the distance r_2 between the two beams getting trough an optical system, (and the tilt θ_2) we have

$$\begin{pmatrix} r_2 \\ \theta_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_1 \\ \theta_1 \end{pmatrix} \tag{2}$$

where (r_1, θ_1) are the input distance and tilt respect to the axis of the optical system.

The waist size $w_0^{(2)}$ instead, is given by the following formula

$$w_0^{(2)} = |A|\, w_0^{(1)} \sqrt{1 + \frac{BC}{AD}}, \tag{3}$$

where $w_0^{(1)}$ is the input waist.

To design a small telescope, we have chosen a confocal doublet with focals $f_1 > 0$ and $f_2 < 0$. With this configuration (see fig. 3), the two lenses lie at a distance $d_2 = f_1 + f_2$ and the input waist $w_0^{(1)}$ at a distance $d_1 = f_1$ from the first lens. The output waist $w_0^{(2)}$ is located in the source space of the second lens at a distance $|f_2|$

For a confocal doublet telescope, the ABCD matrix is

$$\hat{M} = \begin{pmatrix} -\frac{f_2}{f_1} & 0 \\ 0 & -\frac{f_1}{f_2} \end{pmatrix}, \tag{4}$$

and using the (3) we obtain

$$w_0^{(2)} = \left|\frac{f_2}{f_1}\right| w_0^{(1)}. \tag{5}$$

To achieve a waist size $w_0^{(2)} \simeq 1\ mm$, we he have a set of couple of values f_1 and f_2. Because of the very small angular divergence of the input beam ($\theta_\infty \simeq 1.04 \cdot 10^{-4}$), we can neglect the condition $d_1 = f_1$ and in this way the allowed couple of values f_1 and f_2, increases considerably.

A way to reduce as possible the number of optical surfaces, is to use mirrors as focusing elements and in this case a tilt of each mirror (which introduces an astigmatism) is need for folding (see fig. 6).

In this case, considering the tilts of each mirrors M_1, M_2 which are respectively ϕ_1 ϕ_2, the total ABCD matrix that describes the telescope from the input waist $w_0^{(1)}$ to a distance d^* from M_2 will be

$$\hat{M} = \begin{pmatrix} -\frac{f_2'}{f_1'} & \frac{f_2'}{f_1'}(d_1 - f_1') + \frac{f_1'}{f_2'}(d^* - f_2') \\ 0 & -\frac{f_1'}{f_2'} \end{pmatrix} \tag{6}$$

where

$$\begin{aligned} f_i' &= f_i \cos\phi_i, \text{ (Oxz plane)} \\ f_i' &= \frac{f_i}{\cos\phi_i}, \text{ (Oyz plane)} \end{aligned} \qquad i = 1,2 \tag{7}$$

The two beams are considered not overlapped if the following condition is fulfilled

$$\{\text{distance between beams }\} > 2.5\,\{\text{ beam diameter}\}\,. \tag{8}$$

With $f_1 = +1\ m$ and $f_2 = -0.3\ m$ and an incidence angle of $3.08°$ [1] for each mirror, we have the two beams with a radius $w \simeq 1\ mm$ and a separation of $\Delta r = 10.7\ mm$ at a distance $d^* = 770\ mm$.

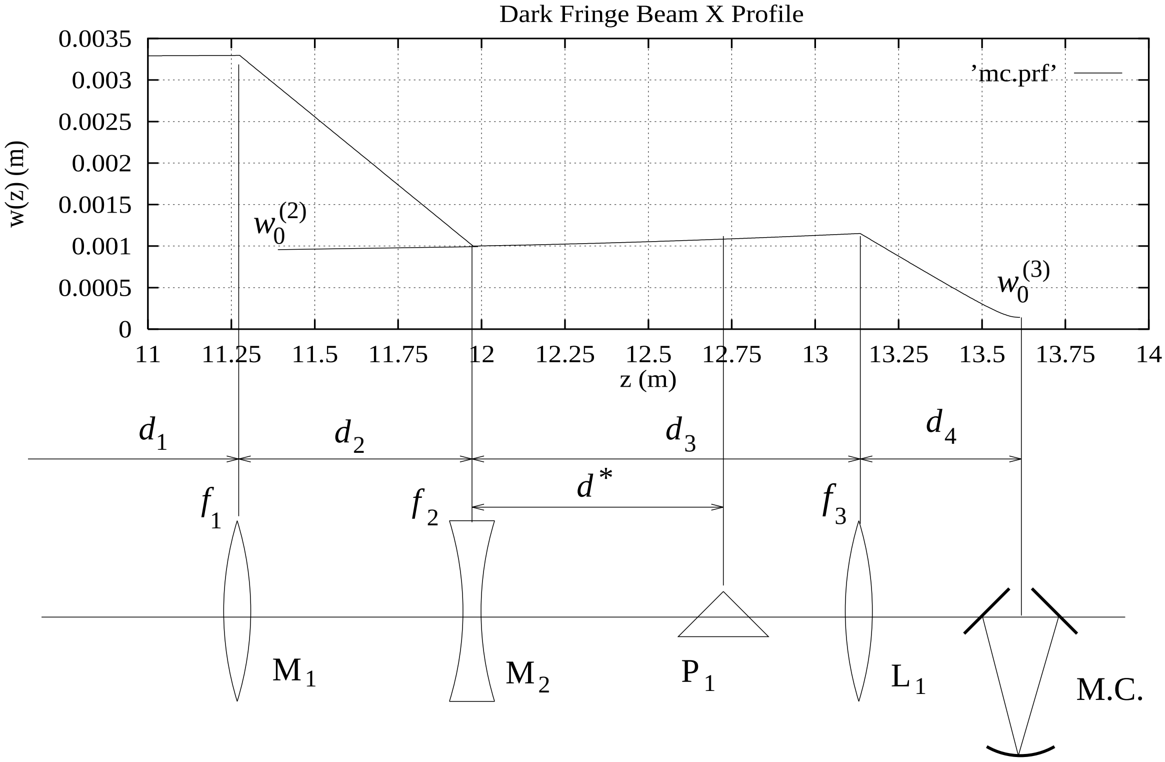

Figure 3: Beam profile. The first waist w_0, is located at 6 m from the reference frame origin.

Adding a lens L_1 of focal $f_3 = +450\ mm$, at a distance $d_3 = 1.16\ m$, we obtain the two waist size (the beam is astigmatic)

$$\begin{aligned} w_0^{(3)} &= 141.36\ \mu m, \quad \text{Oxz plane} \\ w_0^{(3)} &= 138.64\ \mu m, \quad \text{Oyz plane} \end{aligned} \quad \Rightarrow \quad \left\langle w_0^{(3)} \right\rangle = 140.0\ \mu m \tag{9}$$

[1] Angle chosen to simplify the mechanical mounting and the optical alignment of the mirrors and the prism P_1

5 Telescope Losses

The losses due to the spherical aberration for a beam of 3.25 mm and mirrors with focal length greater than 0.3 m are

$$\mathcal{L}_{aber.} < 1.3 \cdot 10^{-6} \tag{10}$$

and they can be neglected [4].

The astigmatism produced by the two tilted mirrors M_1 and M_2, gives a mode mismatch of the mode cleaner. The net effect is a TEM_{00} loss at the mode cleaner output, which is

$$\mathcal{L}_{ast.} \simeq 5.2 \cdot 10^{-4}. \tag{11}$$

(We have considered only the astigmatism produced by the telescope and not the one due to the incidence angle on the mode cleaner face).

Considering an optimistic reflectivity value $R = 99.99\%$, and supposing that all the losses are due to the diffusion, we have

$$\mathcal{L}_{diff.} \sim 10^{-4}, \tag{12}$$

The surface roughness of the mirrors, can be estimated using the following formula [5]

$$\mathcal{L}_{diff.} \simeq \frac{8\pi^2}{\lambda^2}\sigma^2, \tag{13}$$

where λ is the wave length and σ the roughness of the surface. Using the previous value of $\mathcal{L}_{diff.}$, we have

$$\sigma_{rms} \sim 10^{-9} \tag{14}$$

6 Beam Propagation, Main Values

The main input values used for these computations, are here resumed :

input waist size :	$w_0^{(1)} = 3.25 \cdot 10^{-3}\ m$
waist distance from the detection tower center :	$D = 5\ m$
distance between the two beams at the VIRGO beam splitter:	$r_1 = 0.0442\ m$
angle between the two beams :	$\theta_1 = 3.6 \cdot 10^{-3}\ rad$

The optical characteristics of the telescope optics are resumed in the section (8).

In the following table are reported the principal values of the beam propagation in the two orthogonal directions from the beam splitter to the mode cleaner waist position.

x axis

	L	w	R	w0	zw0	r	Theta
	0.0000e+00	3.3096e-03	-1.6811e+02	3.2500e-03	6.0000e+00	4.4200e-02	-3.6000e-03
OmMedium	6.0000e+00	3.2500e-03	7.0066e+09	3.2500e-03	-1.3882e-07	2.2600e-02	-3.6000e-03
OmMedium	1.1000e+01	3.2915e-03	1.9953e+02	3.2500e-03	-5.0000e+00	4.6000e-03	-3.6000e-03
OmMedium	1.1275e+01	3.2962e-03	1.8966e+02	3.2500e-03	-5.2750e+00	3.6100e-03	-3.6000e-03
SphericMir	1.1275e+01	3.2962e-03	-1.0038e+00	1.0309e-04	1.0029e+00	-3.6100e-03	7.2152e-03
OmMedium	1.1975e+01	1.0003e-03	-3.0611e-01	1.0309e-04	3.0286e-01	1.4406e-03	7.2152e-03

SphericMir	1.1975e+01	1.0003e-03	1.4007e+01	9.7874e-04	-5.9655e-01	-1.4406e-03	-1.2024e-02
OmMedium	1.2745e+01	1.0870e-03	7.2207e+00	9.7874e-04	-1.3666e+00	-1.0699e-02	-1.2024e-02
OmMedium	1.2895e+01	1.1106e-03	6.7917e+00	9.7874e-04	-1.5166e+00	-1.2503e-02	-1.2024e-02
OmMedium	1.3135e+01	1.1521e-03	6.3109e+00	9.7874e-04	-1.7566e+00	-1.5389e-02	-1.2024e-02
Lens	1.3135e+01	1.1521e-03	-4.8455e-01	1.4136e-04	4.7726e-01	-1.5389e-02	2.2173e-02
OmMedium	1.3614e+01	1.4142e-04	2.1721e+00	1.4136e-04	-1.6040e-03	-4.7710e-03	2.2173e-02

y axis

	L	w	R	w0	zw0	r	Theta
	0.0000e+00	3.3096e-03	-1.6811e+02	3.2500e-03	6.0000e+00	0.0000e+00	0.0000e+00
OmMedium	6.0000e+00	3.2500e-03	7.0066e+09	3.2500e-03	-1.3882e-07	0.0000e+00	0.0000e+00
OmMedium	1.1000e+01	3.2915e-03	1.9953e+02	3.2500e-03	-5.0000e+00	0.0000e+00	0.0000e+00
OmMedium	1.1275e+01	3.2962e-03	1.8966e+02	3.2500e-03	-5.2750e+00	0.0000e+00	0.0000e+00
SphericMir	1.1275e+01	3.2962e-03	-1.0068e+00	1.0339e-04	1.0058e+00	0.0000e+00	0.0000e+00
OmMedium	1.1975e+01	1.0069e-03	-3.0903e-01	1.0339e-04	3.0577e-01	0.0000e+00	0.0000e+00
SphericMir	1.1975e+01	1.0069e-03	1.0804e+01	9.7035e-04	-7.7031e-01	0.0000e+00	0.0000e+00
OmMedium	1.2745e+01	1.1093e-03	6.5582e+00	9.7035e-04	-1.5403e+00	0.0000e+00	0.0000e+00
OmMedium	1.2895e+01	1.1356e-03	6.2629e+00	9.7035e-04	-1.6903e+00	0.0000e+00	0.0000e+00
OmMedium	1.3135e+01	1.1813e-03	5.9344e+00	9.7035e-04	-1.9303e+00	0.0000e+00	0.0000e+00
Lens	1.3135e+01	1.1813e-03	-4.8692e-01	1.3864e-04	4.8022e-01	0.0000e+00	0.0000e+00
OmMedium	1.3614e+01	1.3868e-04	-2.3750e+00	1.3864e-04	1.3567e-03	0.0000e+00	0.0000e+00

Starting from left to right, each columns contains: the optical device type ; the total path length L the spot size w and the curvature radius R at the opt. device input ; the waist $w0$; the waist position $zw0$ respect to the optical device. The last two columns give the distance r and the angle θ between the two beams.

7 Focal Length Errors

An error on the focal length due to the mirror or lens manufacturing can be easily compensated with the changes of the distances between M_1 and M_2 and between M_2 and L_1.

In spite of that, a maximum error on the focal lengths can be fixed, considering an error of 1% on the mode cleaner waist size, the oder of magnitude of the maximum waist size mismatch allowed.

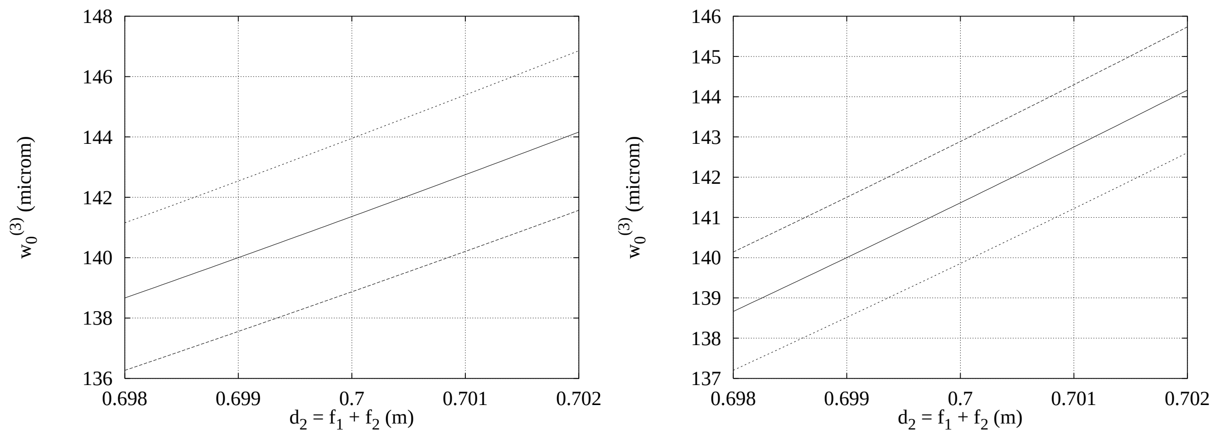

Figure 4: Beam waist $w_0^{(3)}$ (after the lens L_1) as function of the distance d_2 between the mirrors M_1 and M_2. The dashed and dotted lines are for an error $\Delta f/f$ on the focal lengths. $\Delta f_1/f_1 = \pm.2\%$ left figure, $\Delta f_2/f_2 = \pm.5\%$ right figure,

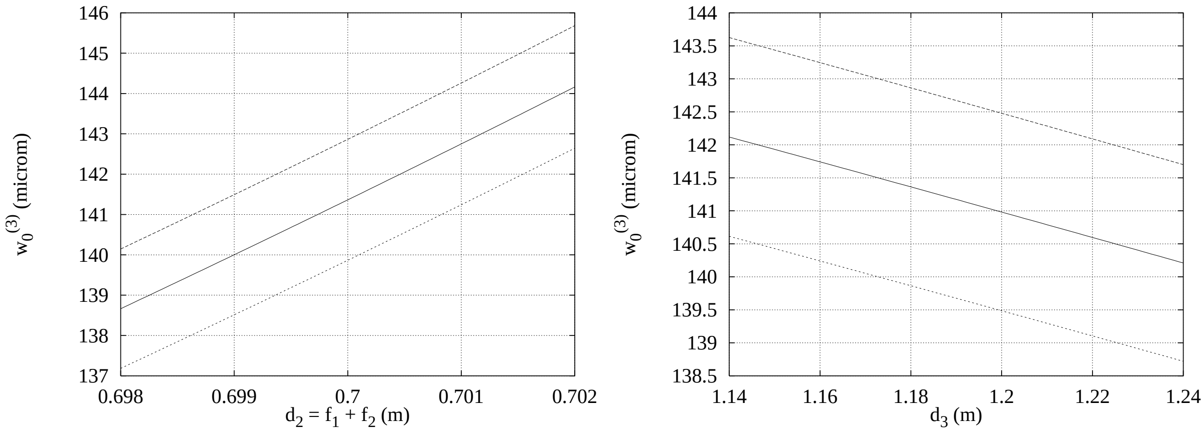

Figure 5: Beam waist $w_0^{(3)}$ (after the lens L_1) as function of the distance d_2 between the mirrors M_1 and M_2 and the distance d_3 between M_2 and the lens L_1. The dashed and dotted lines are for an error $\Delta f_3/f_3 = \pm 1\%$.

In figures 5 and 4, are shown the waist variation $w_0^{(3)}$ as function of d_2 and d_3, for a error on the focal length of M_1, M_2 and L_1.

From those plots, we obtain the sensitivities of the output waist size respect a variation of the distances d_2 and d_3 which are respectively

$$\frac{\Delta w_0^{(3)}}{\Delta d_2} = 1.4 \frac{\mu m}{mm},$$

$$\frac{\Delta w_0^{(3)}}{\Delta d_3} = 0.019 \frac{\mu m}{mm},$$

A length variation of d_2 can be done for a fine matching of the waist mode cleaner and if a very fine adjustment is needed, d_3 could be changed.

8 Detection Bench Telescope Elements Specifications

The complete specification for the main detection bench telescope elements (see fig. 6) are listed in the following table

Device	Mirror M_1	Prism P_1	Mirror M_2	Lens L_1
Incidence Angle	$\sim 3.08°$	$\sim 45°$	$\sim 3.08°$	$0°$
Coating 1^{st}Face (polariz. s)	H.R. (Losses $\sim 10^{-4}$)	H.R. (Losses $\sim 10^{-4}$)	H.R. (Losses $\sim 10^{-4}$)	A.R. (Losses $< 10^{-4}$)
Coating 2^{nd}Face (polariz. s)	None	H.R. (Losses $\sim 10^{-4}$)	None	A.R.
1^{st} Curv. radius	$-(2000 \pm 4)\ mm$	/	$+(600 \pm 3) mm$	/
2^{nd} Curv. radius	∞	/	∞	/
Focal Length	$1000\ mm$	/	$-300\ mm$	$+(450 \pm 5) mm$
Roughness 1^{st}Face (rms)	$\sim 10^{-9}\ m$	$\sim 10^{-9}\ m$	$\sim 10^{-9}\ m$	$\sim 10^{-9}\ m$
Roughness 2^{nd}Face (rms)	un-polished	$\sim 10^{-9}\ m$	un-polished	$\sim 10^{-9}\ m$
Material	Fused Silica	Fused Silica	Fused Silica	Fused Silica
Diameter/side	ø2”	$25\ mm$(side)	ø2”	ø1”
Thickness	$10\ mm$(TBC)	/	$10\ mm$(TBC)	/

References

[1] V. Sannibale, J.-Y. Vinet, **"Cross-Talk" Between the Dark Fringe Beam and the Secondary Beam**, *Virgo Note* VIR-NOT-LAP-1390-063 (1996)

[2] H. Kogelnik e T. Li, **Laser Beam and Resonators**, *Applied Optics* 23 (1966),3.

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[5] P.Hello, **Roughness of the recycling mirror**, *Virgo Note* doc. n^o 0.2 4/10/90 (1990)

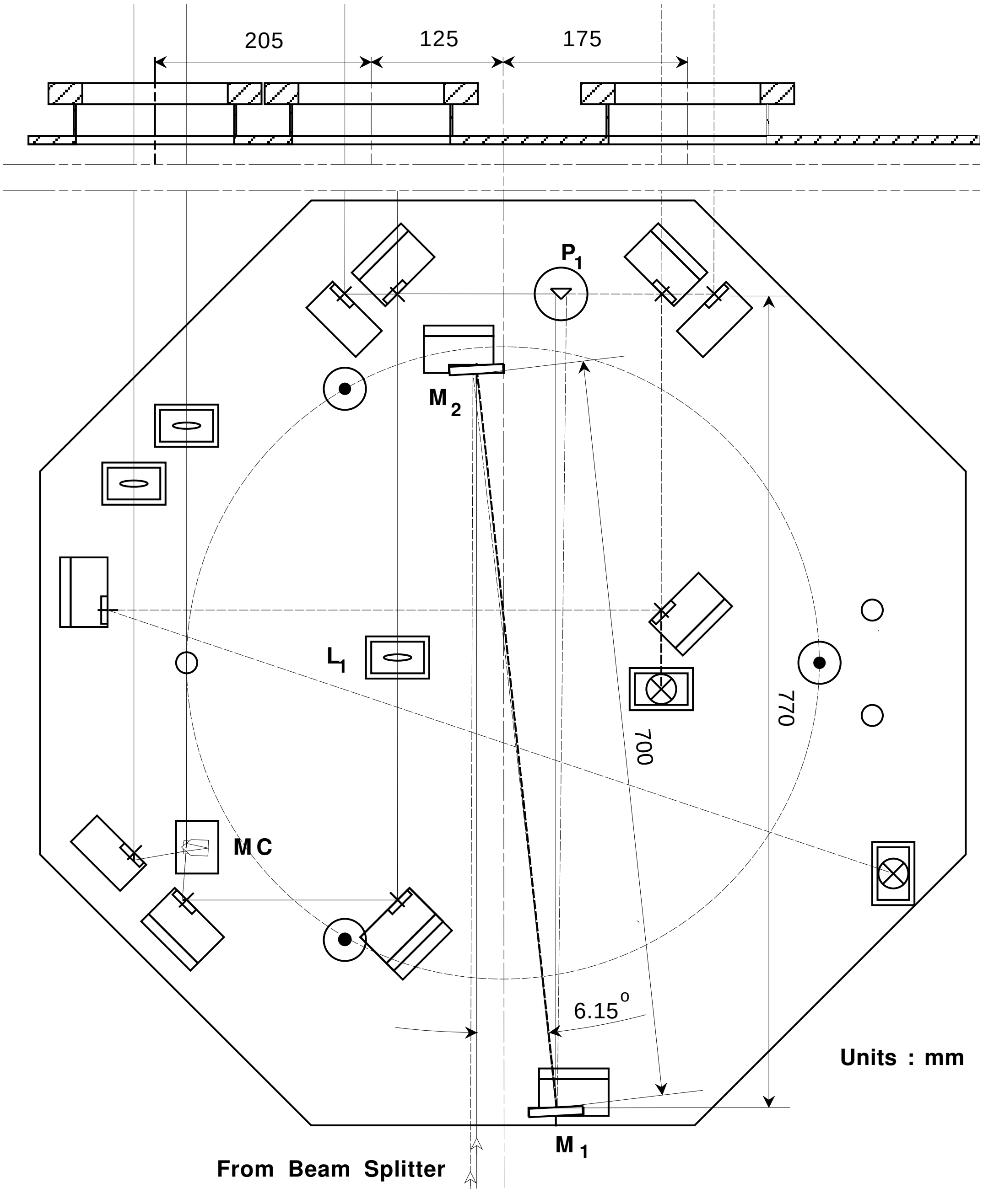

Figure 6: VIRGO98 Detection bench layout. The telescope optical elements are M_1 P_1 M_2 and L_1. The dark-fringe beam is the continuous line and the secondary beam is the dashed one.