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VLT PROGRAMME

VERY LARGE TELESCOPE

Macao VLTI
Wavefront Sensor Optics

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TABLE OF CONTENTS

1. INTRODUCTION

ESO intends to use curvature sensing adaptive optics facilities on several VLT instruments :

- MACAO VLTI (4 units)
- SINFONI (1 unit)
- CRIRES (1unit)

Although all 3 instruments have different incoming F/N and requirements, they will use the same wavefront sensor.
The nominal incoming F/N of the system has been set up by the first instrument (Macao VLTI). This instrument is the only one, which can be operated without additional front optics to slow down the beam; the membrane mirror has to be operated with a F/N around 50. The two other instruments have F/N around F/15. Both will use a relay optic to obtain a F/46.7 beam on the membrane mirror.

2 OVERVIEW OF THE SYSTEM

The wavefront sensor consists of mainly 4 units, which are :

- A membrane mirror located on the telescope image.
- A wavefront sensor box
- A lenslet array located on a pupil image
- A detector system which includes optical fibres and APDs.

The image of the telescope focus is formed on a membrane mirror either directly for MACAO or through relay optics for CRIRES and SINFONI. The beam F/N is F/46.7 and the field of view is 3 arcsec on the sky (or 5.44 mm linear on the mirror). This mirror will vibrate at a frequency of 2.1 kHz to create intra and extra defocused beams on the lenslet array (location where the analysis is done). The beams, which reach the membrane mirror, are telecentric.
Between the membrane mirror and the lenslet array, a relay optic is necessary to collimate the beam and to form an image of the pupil (corresponding to the deformable mirror) on the lenslet array. This unit has been called “wavefront sensor box”.
The lenslet array divides the pupil in 60 different sub-apertures arranged on a circular geometry which matches the actuators of the deformable mirror. Each lens of the array produces an image of the 3 arcsec field on a common focal plane.
These 60 images are collected by 60 fibres, and then, transferred to a detector, which consists of 60 APDs.

3 THE MEMBRANE MIRROR

The membrane mirror vibrates at a frequency of 2.1 kHz
The maximum radii of curvatures, which should be reached by the mirror are between infinity +/- 500mm. The influence of the curvature variation of the membrane mirror on the rest of the wavefront sensor optics is shown in paragraph 5.

In the case of MACAO this mirror will be mounted on a translation unit to offer the possibility to modify the focus position of the Coudé focus.

4 THE WAVEFRONT SENSOR BOX

4.1 Remark

We have selected the laser writing technology for the manufacturing of the lenslet array. For the PDR we had the choice between 28 and 14 mm pupil diameters. As the laser writing can only deal with the14 mm pupil, the 28 mm pupil will not be considered anymore in the report.
The lenses will be moulded or replicated on plastics.
This fabrication method is only applicable for a sag below 20 to 25 µm. In order to be compatible with this limitation we will use a two lenslet arrays concept.

The following table lists the 1st order properties of the system:

	14 mm pupil
Focal length of the sensor box	654
Linear sensor box F.O.V for 3 arcsec on the sky	5.44 mm
Angular sensor box F.O.V. for 3 arcsec on the sky	0.467º

Another modification of the system in the introduction of an optical derotator in front of the lenslets arrays. This will avoid the rotation of the APD's as foreseen in the original concept

4.2 Description

The wavefront sensor box consists of 4 mirrors, which provides a 14mm (diameter) parallel beam starting from a F/46.7 beam.
The incoming light is reflected by the membrane mirror. This beam is then, collimated by the mirror SBM1. This mirror is spherical and tilted be 3º. The second mirror SBM2 folds the beam and send it to the beam expander, which includes the mirror SBM3 and SBM4. Both mirrors are off-axis parabolas, they produces a 14 mm parallel beam starting from a 4.67mm beam. This mirror combination re-images the pupil at an accessible location in the parallel beam. An optical derotator in the parallel beam is used to compensate for the pupil rotation. The layout of the wavefront sensor box is shown in Fig 4.1

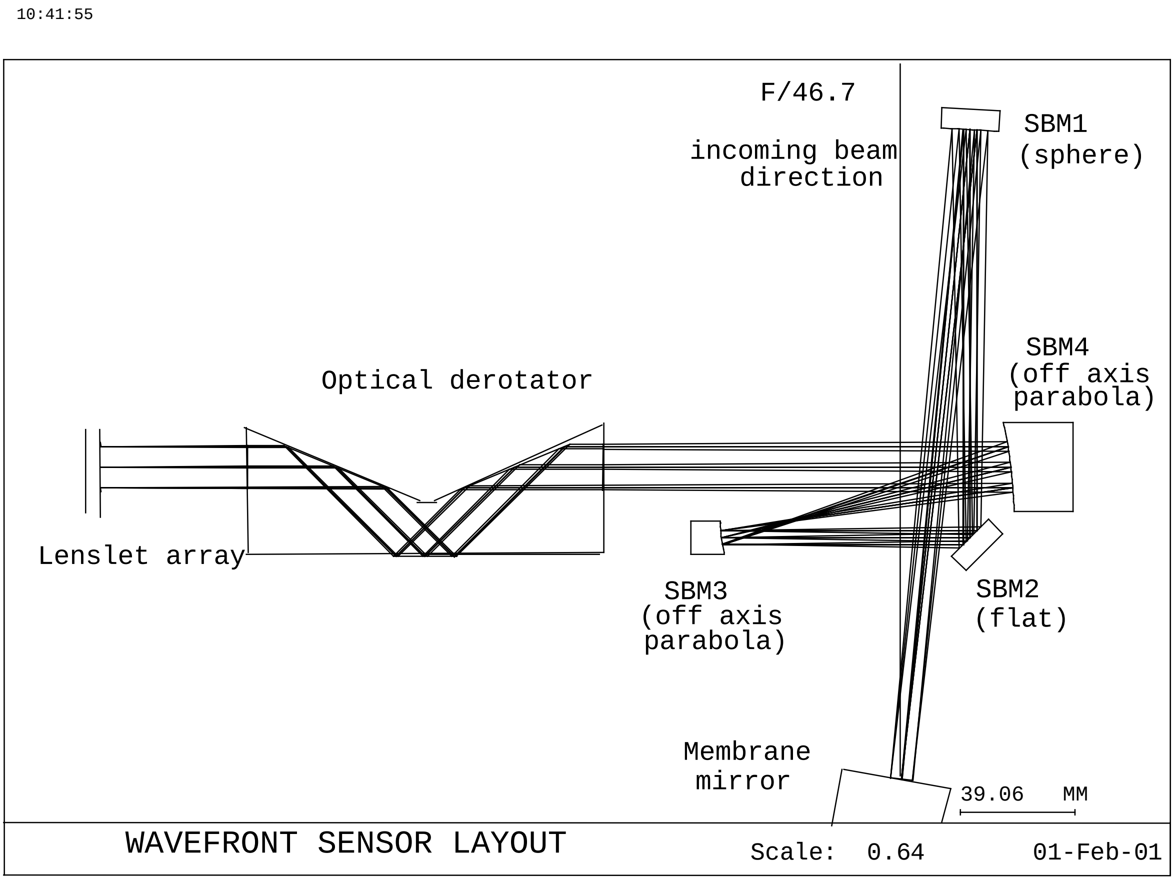


Fig 4.1

4.3 Optical prescriptions

Entrance pupil diameter: 21410 mm
Exit pupil diameter: 14 mm
Field of view: 7.5 mm (diameter)
Effective focal length: 654 m

Surface	Radius of curv.	Tilt –Decentering	Thickness	Medium	Diam.
Object	-	-	-1000000	Air	-
Pupil	-		1000000	Air	-
Membrane mirror	-	-	220.0	Refl	-
4 SBM1	440	3º	137.0	Refl	13
5 SBM2	-	45º	80.0	Refl	13
6 SBM3	50.0 (parabola)	-6.0 mm	100.0	Refl	7
7 SBM4	150.0 (parabola)	18.0 mm	310.8 *	Refl	22
8 Pupil	-	-	Infinity	Air	-
9 Image	-	-	-	Air	-

*This distance is between SBM4 and the lenslet array. The optical path is 335 mm.

4.4 Beam footprints

The next figures (4.2 to 4.5) show the footprint on the mirrors for 5 field positions (axis and +/- 3.76 mm in X and Y directions)

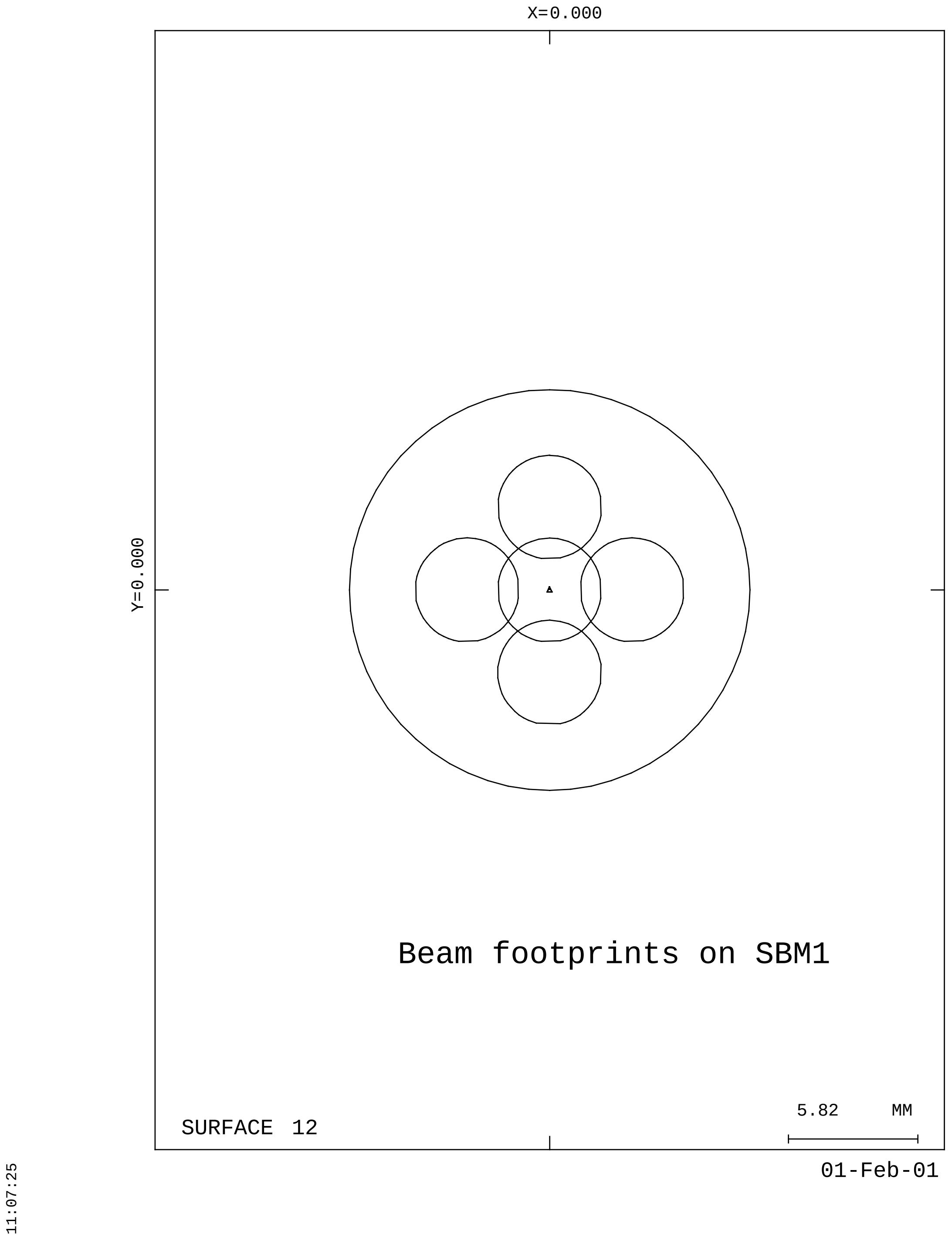

X=0.000
Y=0.000
Beam footprints on SBM1
SURFACE 12
5.82 MM
01-Feb-01
11:07:25

Fig 4.2

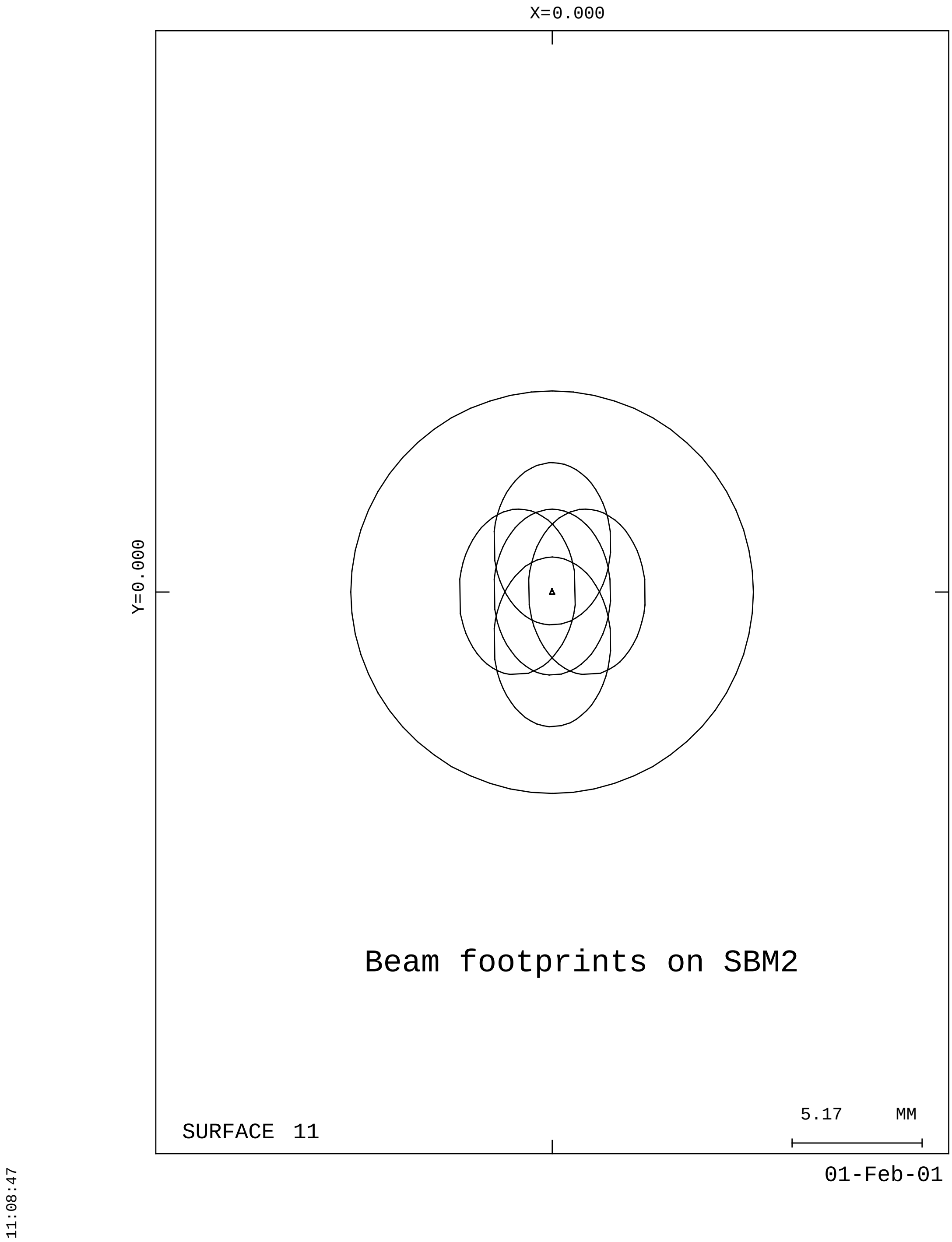
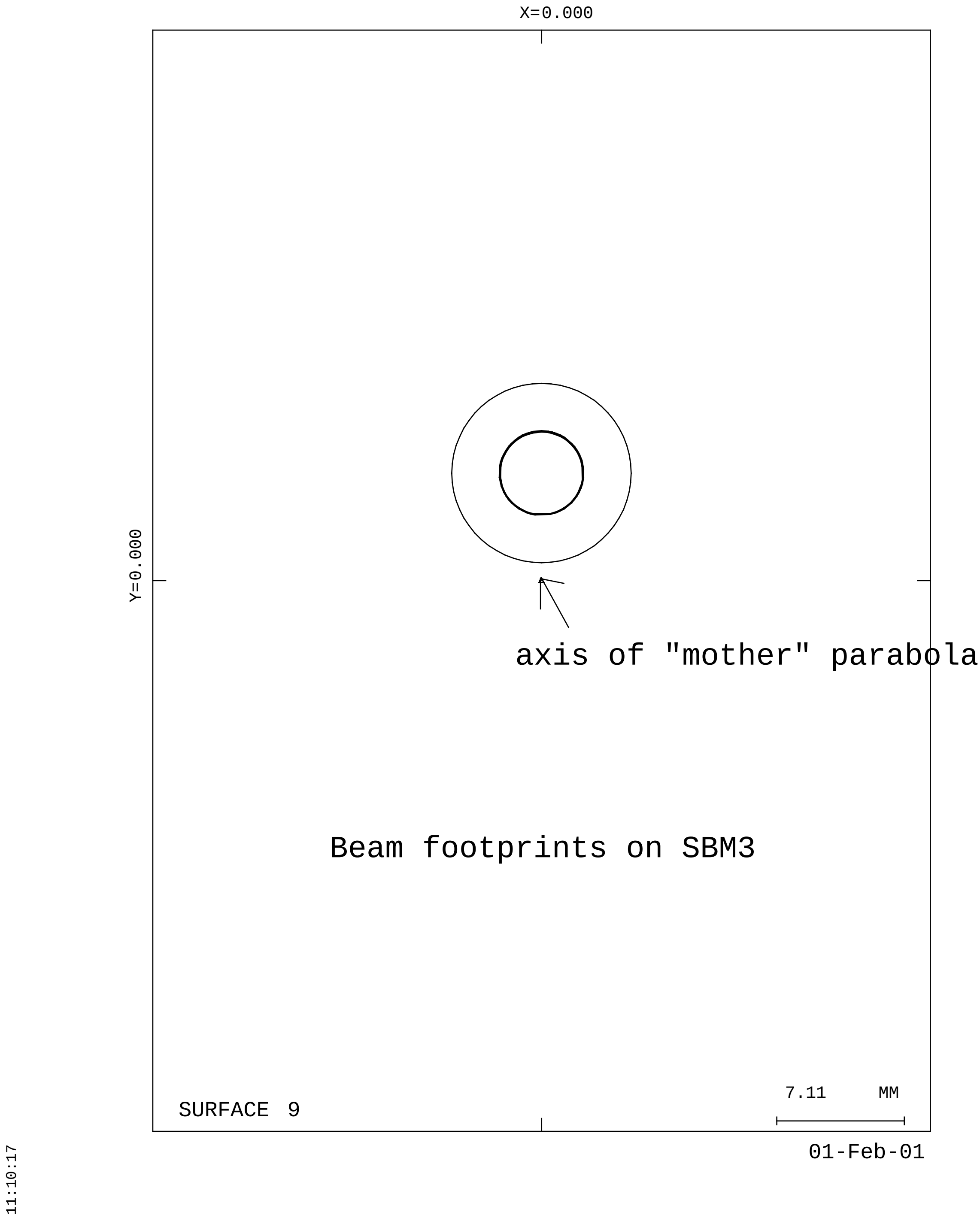

X=0.000
Y=0.000
Beam footprints on SBM2
SURFACE 11
5.17 MM
01-Feb-01
11:08:47

Fig 4.3



X=0.000
Y=0.000
axis of "mother" parabola
Beam footprints on SBM3
SURFACE 9
7.11 MM
01-Feb-01
11:10:17

Fig 4.4

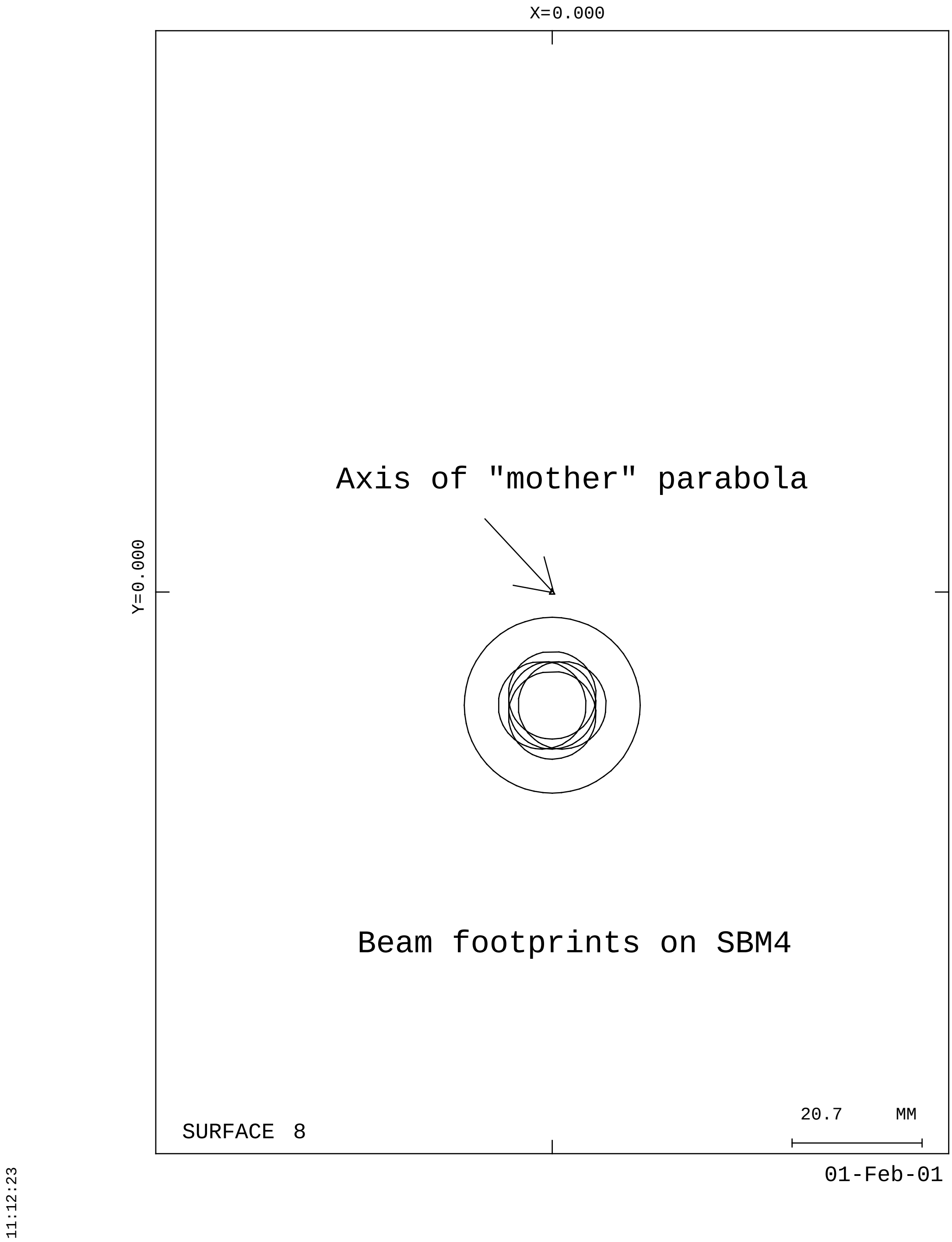

X=0.000
Y=0.000
Axis of "mother" parabola
Beam footprints on SBM4
SURFACE 8
20.7 MM
01-Feb-01
11:12:23

Fig 4.5

4.5 Optical quality

Imaging

The following spot diagrams (Fig 4.6) show the image quality of the wavefront sensor box. These spot diagrams are shown at the membrane mirror focus, starting from a 14mm parallel beam. These spot diagrams are geometrical; the system is fully diffraction limited.

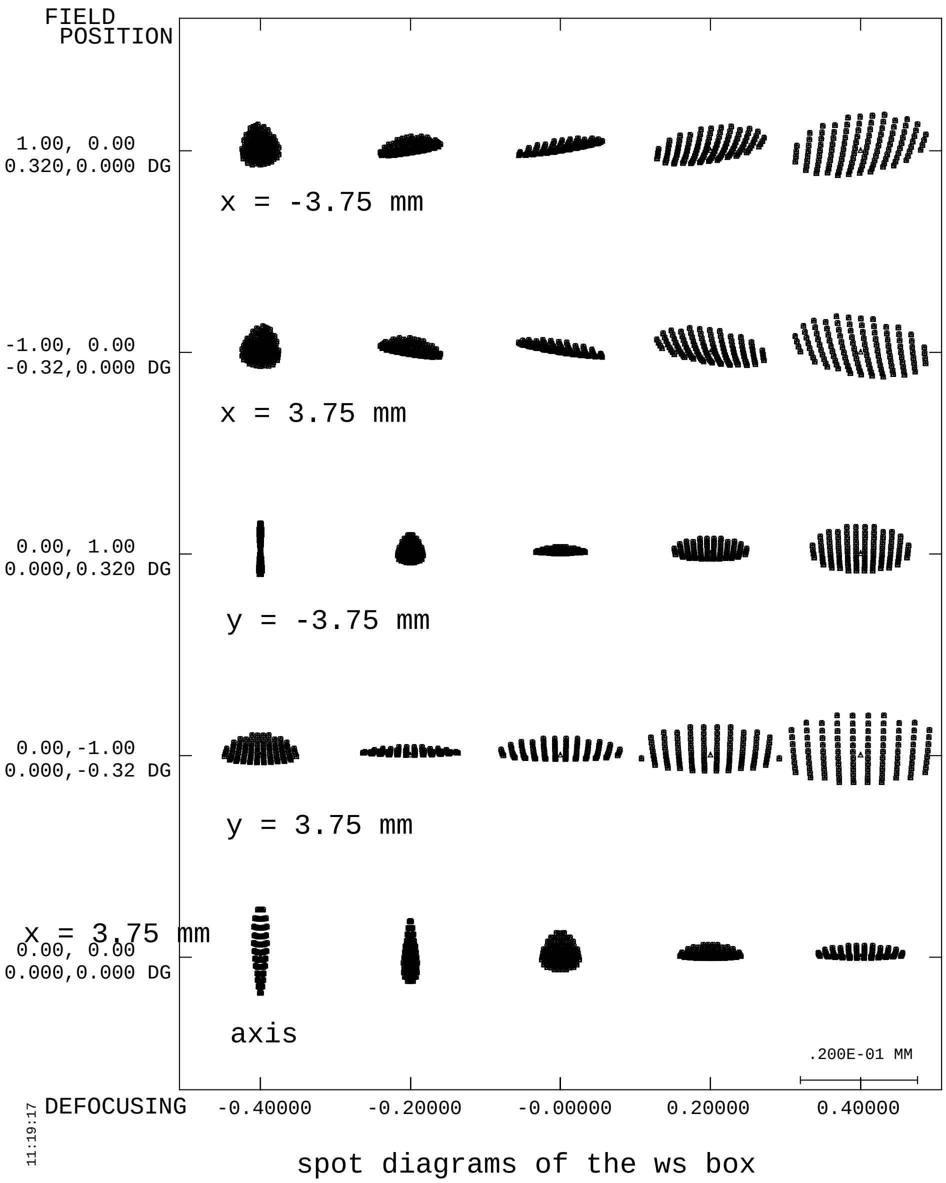


Fig 4.6

Pupil imaging

A good image of the pupil is necessary to be sure to have the measurement points on the exit pupil corresponding to the actuators of the AO mirror.
The following table shows the matching between the deformable mirror and the exit pupil of the wavefront sensor box. All optics are included.

MACAO VLTI :

Relative pupil Position		Position in mm On deformable Mirror		Position in mm On exit pupil		Magnification
X	Y	X	Y	X	Y	
0.0	-1.0	0.000	-50.657	-0.003	-7.066	7.1691
0.0	-0.8	0.000	-40.503	-0.002	-5.652	7.1661
0.0	-0.6	0.000	-30.361	-0.001	-4.238	7.1640
0.0	-0.4	0.000	-20.230	0.000	-2.824	7.1636
0.0	-0.2	0.000	-10.110	0.000	-1.410	7.1702
0.0	0.2	0.000	10.101	0.000	1.417	7.1290
0.0	0.4	0.000	20.194	0.000	2.830	7.1357
0.0	0.6	0.000	30.280	-0.001	4.245	7.1331
0.0	0.8	0.000	40.358	-0.002	5.659	7.1316
0.0	1.0	0.000	50.431	-0.003	7.073	7.1300
1.0	0.0	49.162	0.007	7.017	0.000	7.0061
0.8	0.0	39.325	0.004	5.613	0.000	7.0060
0.6	0.0	29.492	0.002	4.210	0.000	7.0052
0.4	0.0	19.660	0.001	2.806	0.000	7.0064
0.2	0.0	9.830	0.000	1.403	0.000	7.0063
0.0	0.0	0.000	0.000	0.000	0.000	-

The magnification between the exit pupil and the deformable mirror is
- 7.15 in Y direction
- 7.01 in X direction

The largest contribution to this difference is due to the tilt of the deformable mirror. Otherwise we can consider than the light distribution on the exit pupil matches very well the deformable mirror. These values are given for a star on the centre of the field of view.

4.6 Sensitivity analysis of the box

The following table shows the sensitivity of the mirrors inside the box for decenterings of 0.1 mm and tilts of 1 arcmin
Values are in mm; the analysis describes the field displacement at the membrane mirror (assuming a parallel beam issued from the lenslet array)

SBM1	RMS wavefront	X	Y	Z
DX	7 (nm)	0.100	-	-
DY	7	-	0.100	-
DZ	7	-	0.005	0.100
D alpha	7	-	-0.128	-
D beta	7	0.128	-	-
D gamma	7	-	-	-

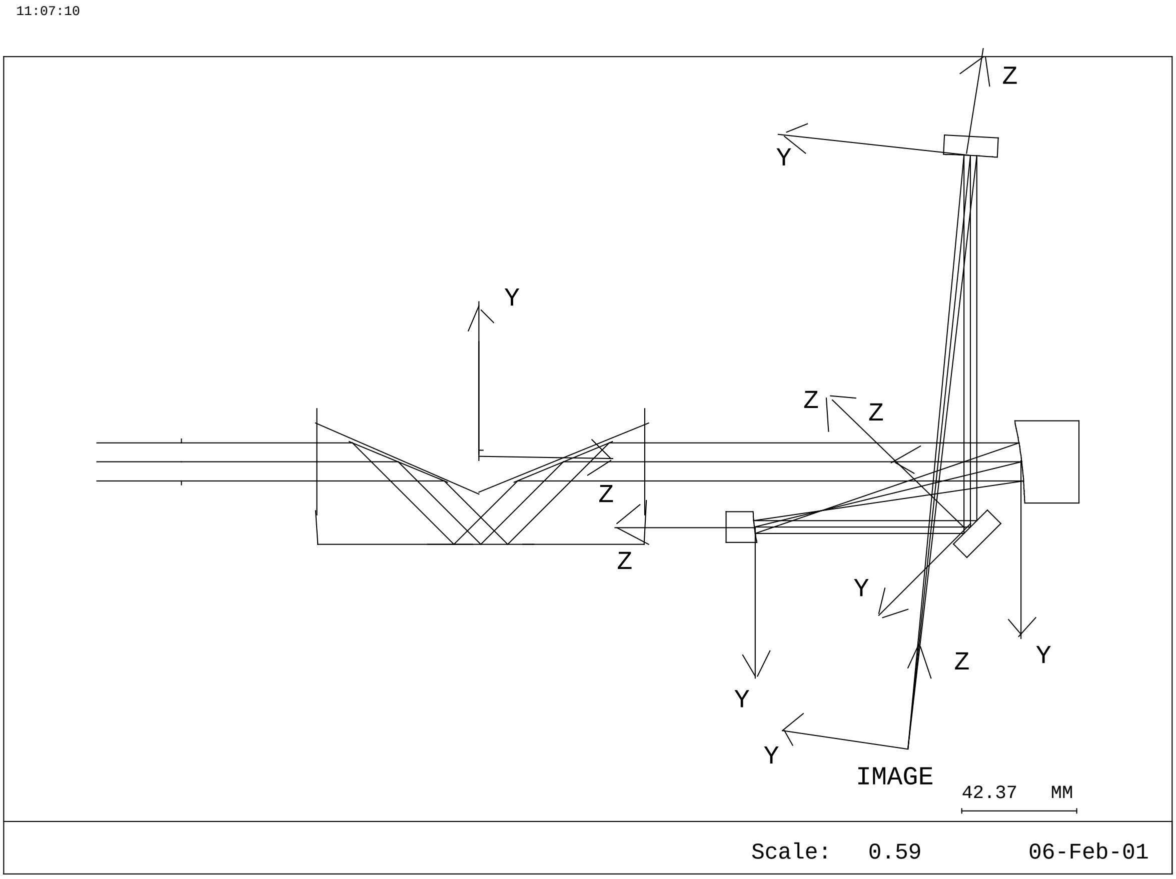
SBM2	RMS wavefront	X	Y	Z
DX	7	-	-	-
DY	7	-	-	-
DZ	7	-	-	-
D alpha	7	-	0.128	-
D beta	7	-0.091	-	-
D gamma	7	-	-	-

SBM3	RMS wavefront	X	Y	Z
DX	23	0.869	-	-0.015
DY	28	-	0.842	1.714
DZ	2	-	-0.205	7.274
D alpha	5	-	-0.129	-
D beta	7	0.127	-	-
D gamma	7	0.015	-	-

SBM4	RMS wavefront	X	Y	Z
DX	23	-0.868	-	-0.024
DY	14	-	-0.841	-1.759
DZ	12	-	0.205	-7.340
D alpha	2	-	-0.386	-
D beta	9	0.382	-	-
D gamma	7	0.045	-	-

DEROT.	RMS wavefront	X	Y	Z
DX	7	-	-	-
DY	7	-	-	-
DZ	7	-	-	-
D alpha	7	-	0.384	-0.021
D beta	7	-0.384	-	-
D gamma	7	-	-	-

The reference axis of the system are shown in the following figure:



1st order parameters

Influence of 1% error on curvature radius (f/n nominal 47.14)

MIRRORS	Rms wavefront error (in nm)	Defocusing (mm)	F/N	Exit pupil position (mm)
SBM1	7	2.0	47.58	23800
SBM2	-	-	47.14	39000000
SBM3	21	18	47.11	23000000
SBM4	46	56	49.00	41300

Influence of 0.1mm error on distances

DISTANCES	Rms wavefront error (in nm)	Defocusing (mm)	F/N	Exit pupil position (mm)
M1-M2	7	-	47.14	575000
M2-M3	7	-	47.15	575000
M3-M4	2	7.3	46.97	622000

5 THE LENSLET ARRAY

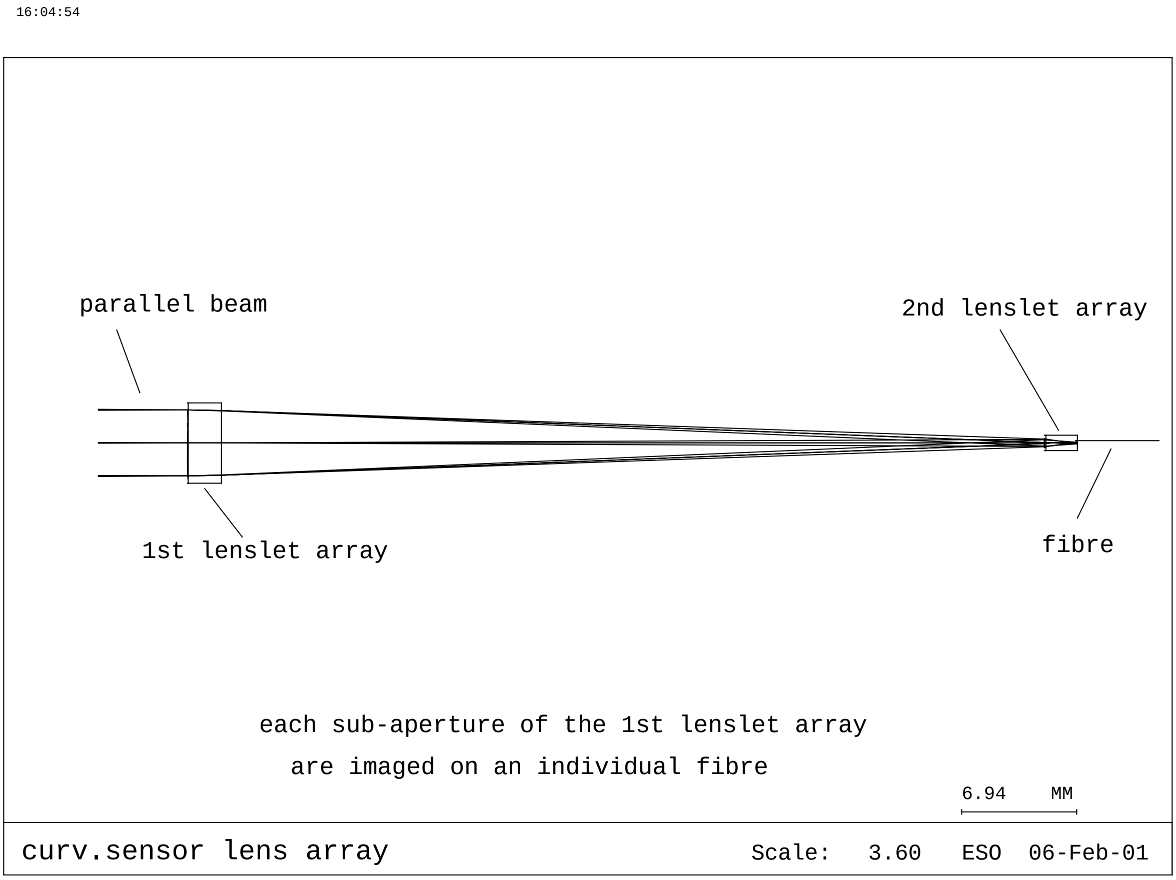
5.1 Description

The laser writing technology can only achieve a sag of 20µm if we want to maintain an excellent surface roughness which should prevent us from straylight or light losses. In order to deal with this strong constraint we had to make the following modifications with respect to the original design:

- Reduction of the pupil diameter to 14 mm
- Split of converging power between 2 lenslets arrays

Instead of the field of view, it is now the sub-pupils of the first lenslets array, which are now imaged by the second lenslets array on the fibre entrance. This concept has the advantage to provide a spot diameter which does not depends of the field of view. Only the F/N in the fibre will depend of the field of view. This solution has probably a better stability.

The following figure shows the principle of the system :



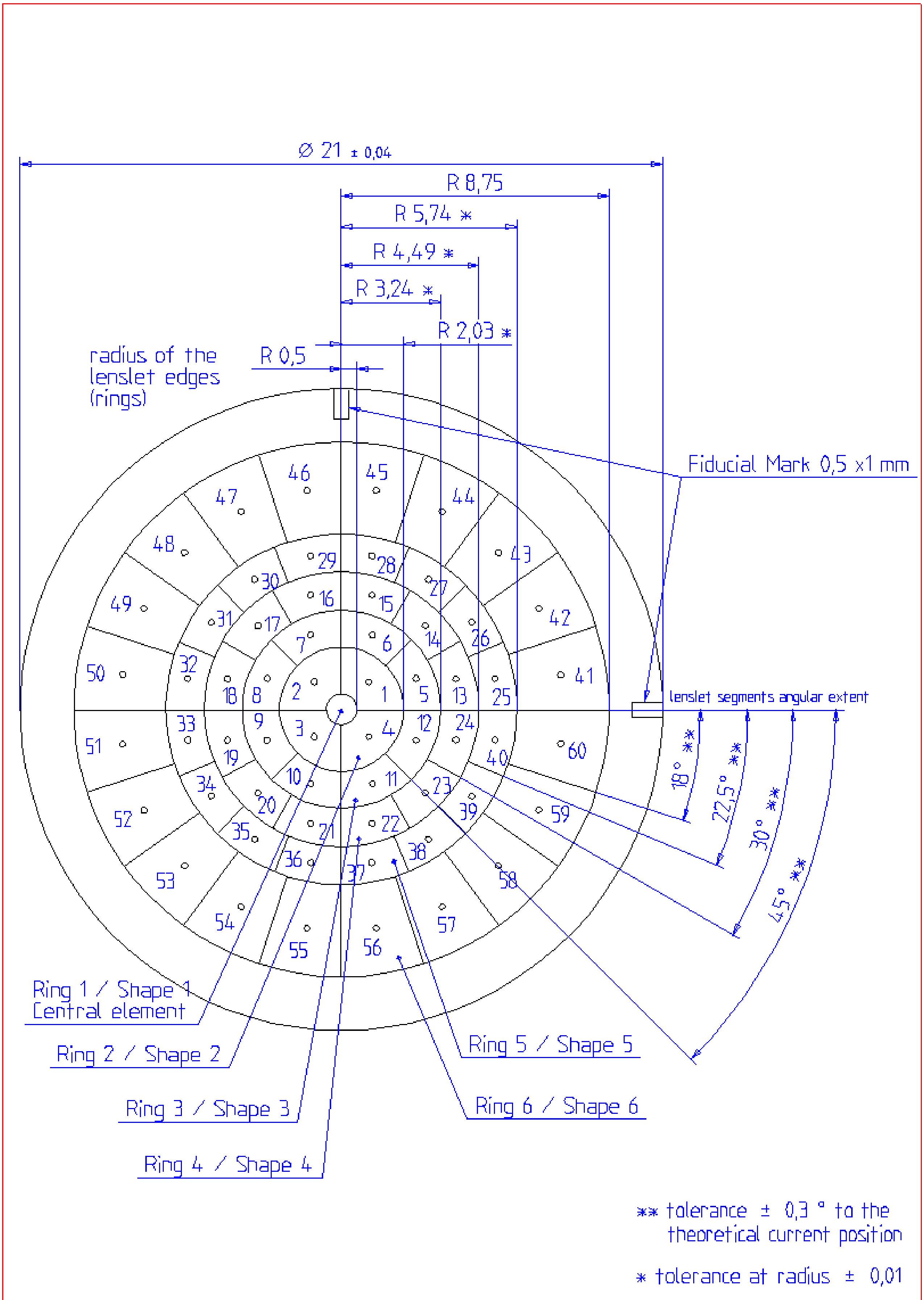
The first lenslet array requires a radius of curvature of 29 mm for the lenslets. The maximum distance from the lenslet edge to the lenslet center is :

- 1.25 mm for the lenslet located in the central area
- 1.90 mm for the lenslet located on the outer ring.

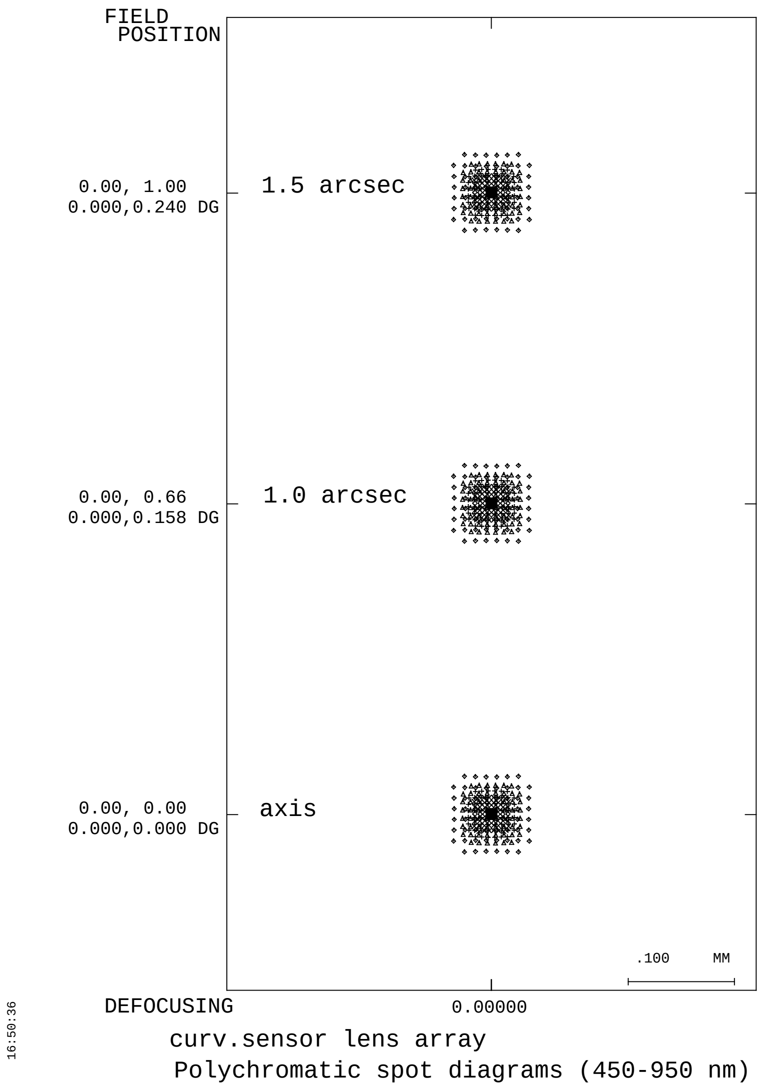
These values corresponds respectively to a maximum sag of :

- 27 µm
- 62 µm

For both cases the maximum sag of 20 µm is not respected. Fresnel lenses will be required, 2 steps for the central area and 3 steps for the outer ring.


Ø 21 ± 0,04
R 8,75
R 5,74 *
R 4,49 *
R 3,24 *
R 2,03 *
R 0,5
radius of the lenslet edges (rings)
Fiducial Mark 0,5 x1 mm
lenslet segments angular extent
18° **
22,5° **
30° **
45° **
Ring 1 / Shape 1 Central element
Ring 2 / Shape 2
Ring 3 / Shape 3
Ring 4 / Shape 4
Ring 5 / Shape 5
Ring 6 / Shape 6
** tolerance ± 0,3 ° to the theoretical current position
* tolerance at radius ± 0,01

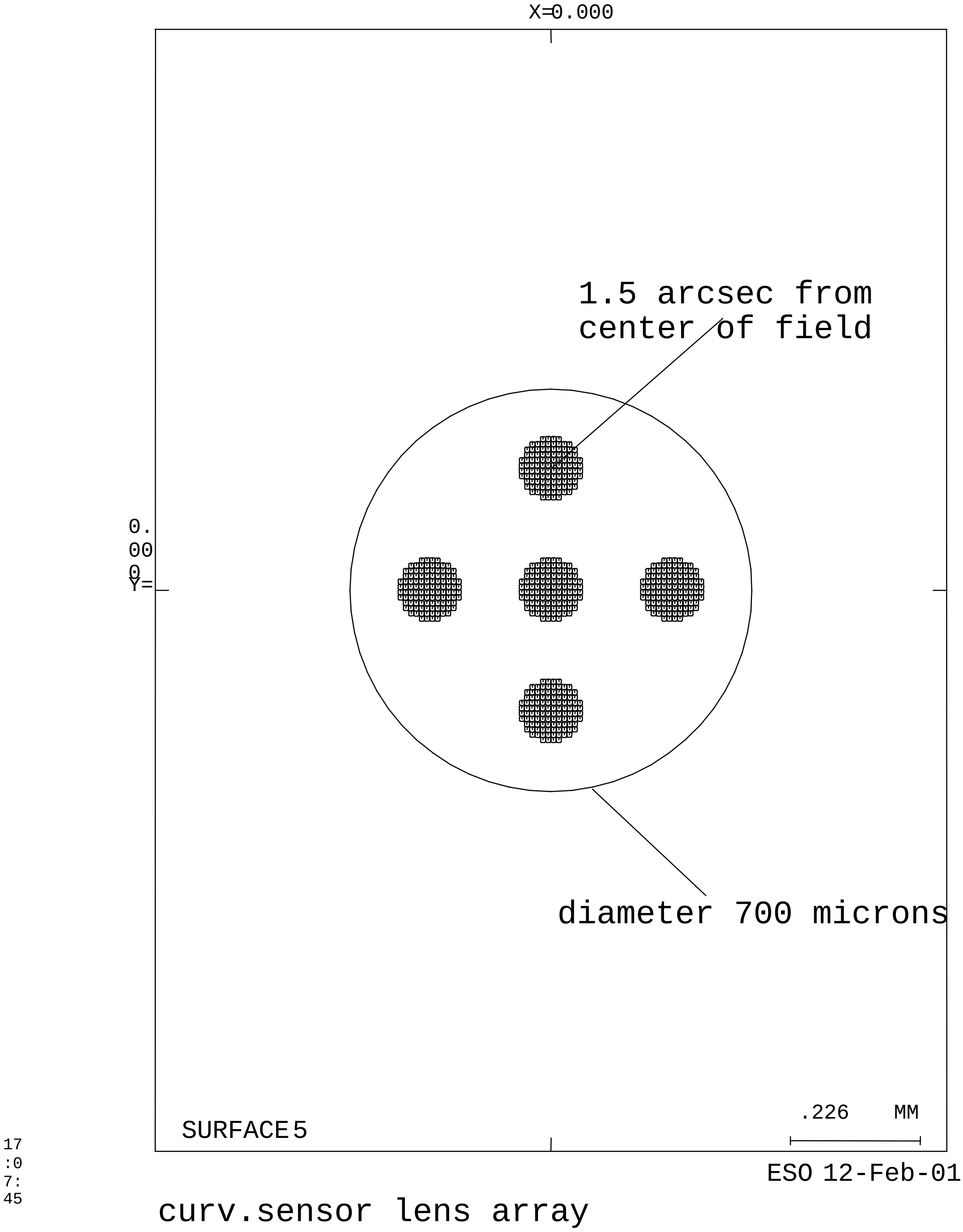
The first lenslet array will provide an image of the star, the quality of this image is shown on the following spot diagram . The maximum F/N has been considered for the spot diagrams (F/13.6)



curv.sensor lens array
Polychromatic spot diagrams (450-950 nm)

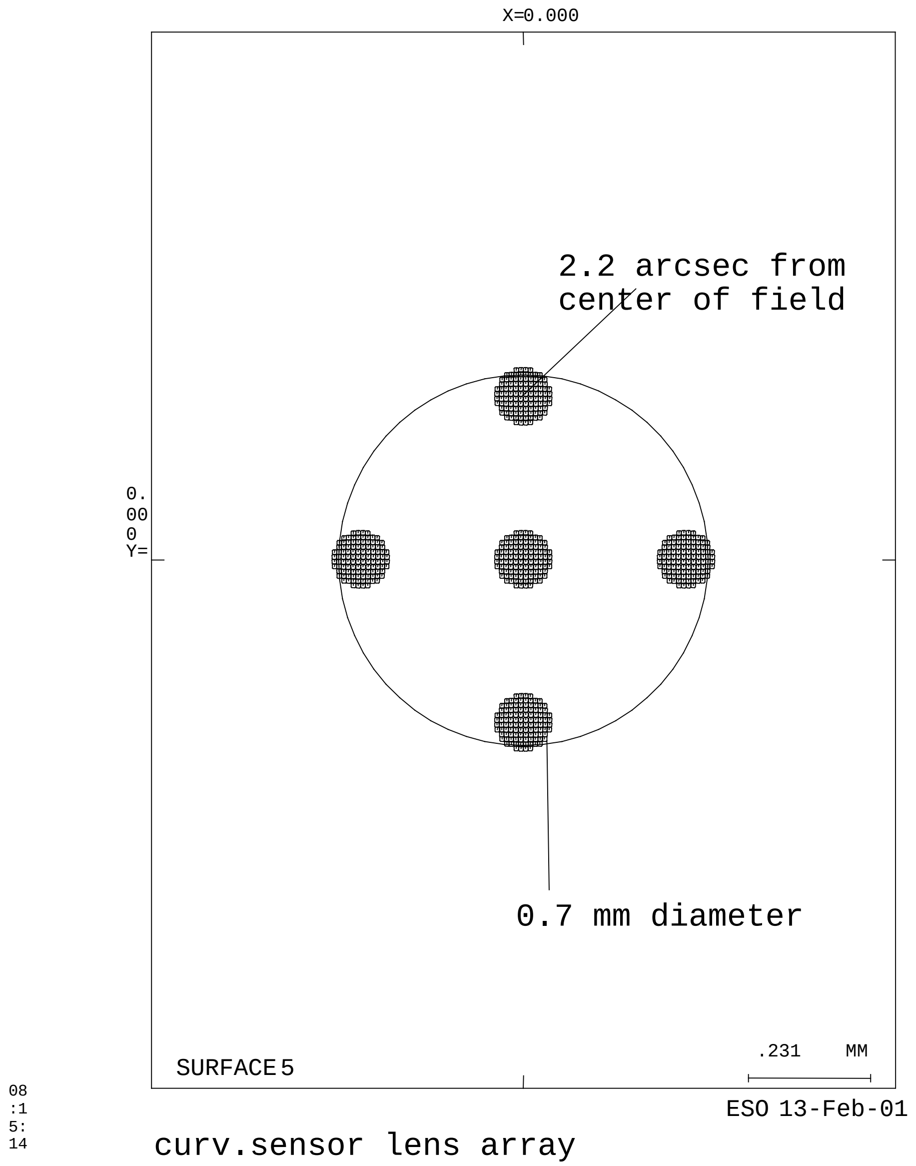
The second lenslet array will be located in front of the image provided by the 1st lenslet array. The following figures shows the beam footprints corresponding to stars located on axis and at +/- 1.5 arcsec in X and Y direction.

DRAWING OF 2ND LENSLET ARRAY TO BE INSERTED



beam footprint on 2nd lenslet array

The diameter of the individual lenslet of the 2nd array is 0.7 mm. The maximum F.O.V., which can be accepted without vignetting is shown in the next figure:



beam footprint on the 2nd lenslet array

5.2 Parameter of the system

1st lenslet array

- Lens radius: 29 mm
- Material: optical bound NAO61
- Thickness of the substract: 50µm
- Support plate material: Silica
- Thickness of the support: 2 mm (not a constraint)

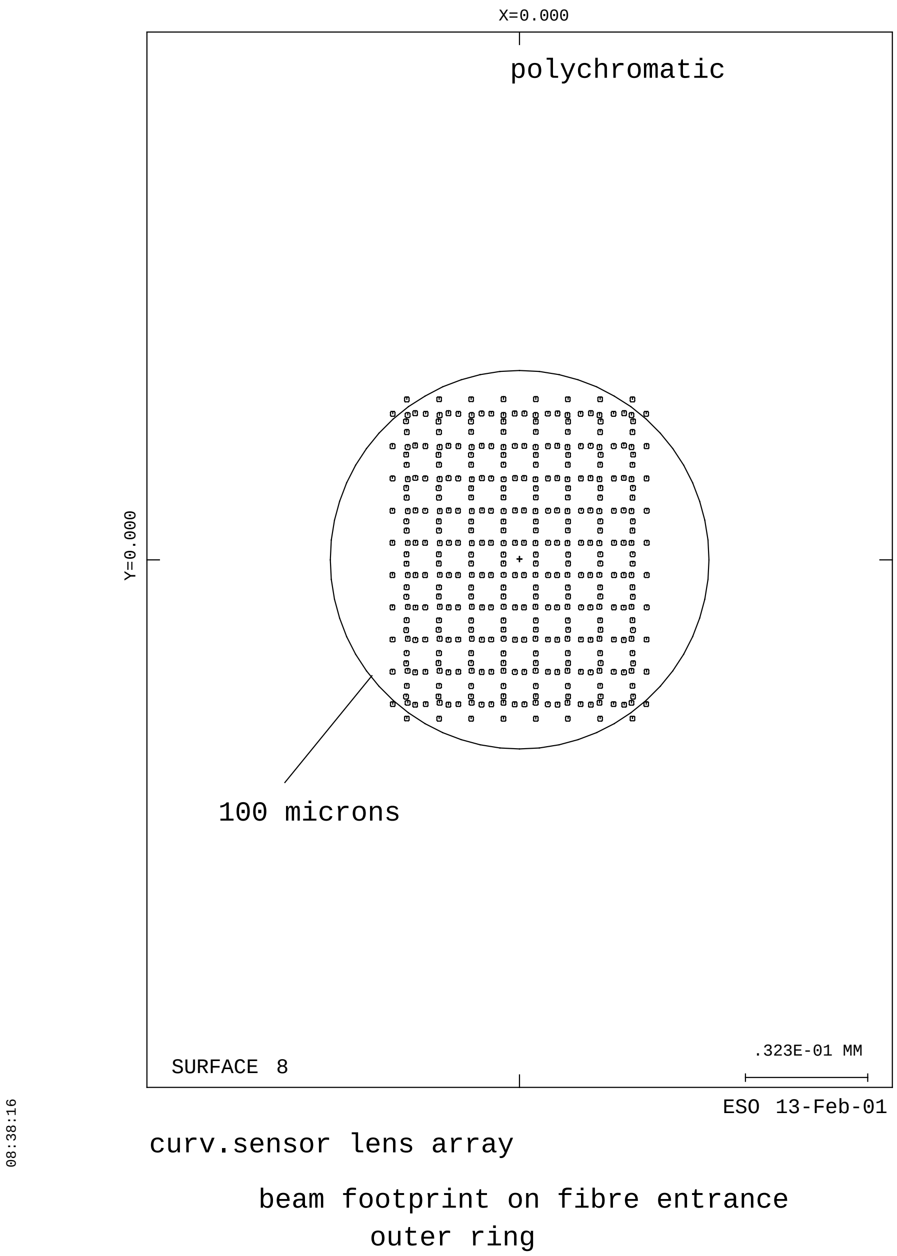
- Distance between silica plate back surface and 2nd lenslet array: 49 mm

2nd lenslet array

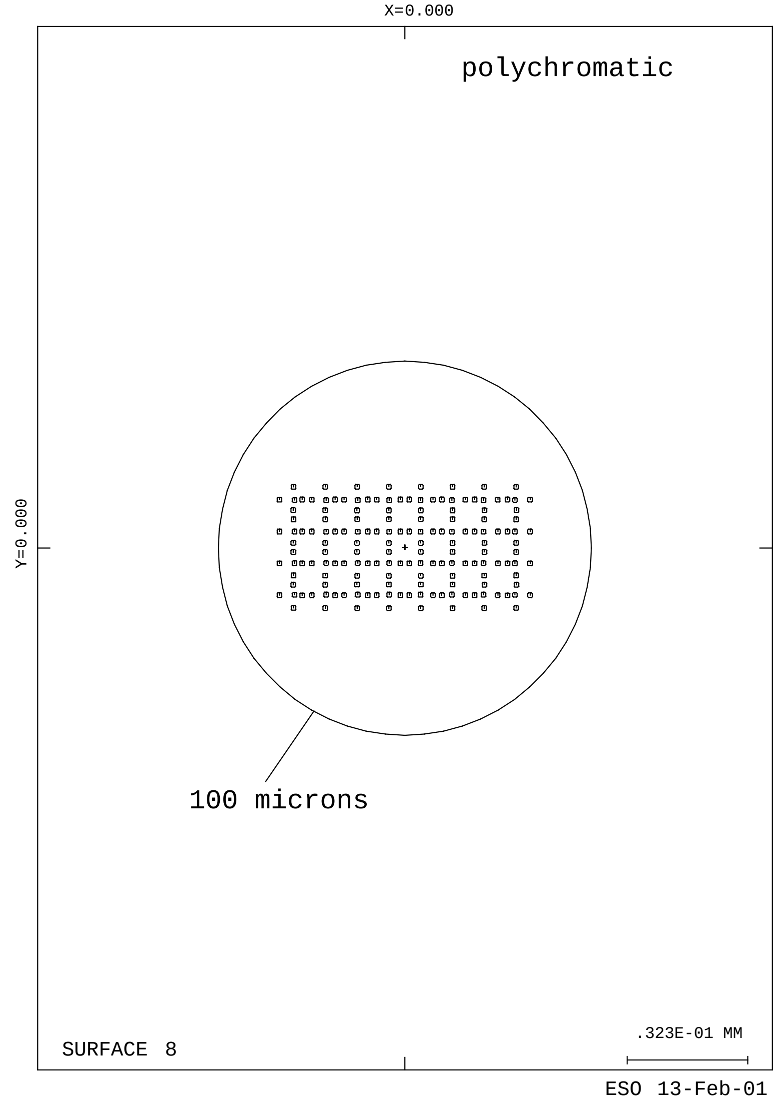
- Lens radius: 0.75 mm
- Material : optical bound NA061
- Thickness of substract : 50 µm
- Support plate material : Silica
- Thickness of the support: 1.85 mm
- Fibre diameter: 100µm

5.3 Performances of the system:

The following figures shows the image of a sub pupil of the outer ring (approximated to 2.6 x 3.0 mm) on the fibre entrance. The F.O.V. is 3 arcsec and the image is polychromatic



The next figure is for the inner ring (approximated to 2.4 x1.4 mm). The conditions are identical to the previous one.



08:52:55

curv.sensor lens array

beam footprints on fibre entrance

inner ring

The entrance F/N in the fibre is in this configuration field dependant. The value of F/2 (in air) is achieved for a F.O.V. of 4.4 arcsec corresponding to the full diameter of the second individual lenslet. For the 3 arcsec field of view the F/N in air is F/3.

5.4 Influence of fabrication errors on the system performances:

- Error of 0.5 mm on radius of 1st lenslet : 2 μm monochromatic additional image size on the fibre. (this value in negligible if we include chromatism)

- Error of 0.5 mm on distance between the 2 lenslet array: the image size variation on the fibre is negligible
- Error of 50µm on 2nd lenslet radius: 8 µm additional image size on the fibre.
- Error of 0.1 mm on 2nd lenslet thickness: 10µm additional image size on the fibre
- Decentering of 50µm of the 1st lenslet array: 1µm decentering of the image on the fibre. This parameter is not influent because the pupil is imaged on the fibre. It leads only to an asymmetry of the F.O.V. on the second lenslet array.
- Tilt of 10arcmin of the 1st lenslet around its vertex: negligible.
- Tilt of 10 arcmin of the 2nd lenslet array + fibre around its vertex: 4 µm decentering of the image on the fibre.
- Decentering of 5µm between the 2nd lenslet array and the fibre: 5µm of the image on the fibre

6 INFLUENCE OF THE MEMBRANE MIRROR

The variation of the radius of curvature of the membrane mirror implies a reduction of the field of view of the wavefront sensor during operation.
The lenslet array is the optical element, which limits the F.O.V. Its collecting area is 17.5 mm. The rest of the wavefront sensor box has been sized considering this diameter and an angular field of 0.35º (4.4 arcsec on the sky).
When the membrane mirror is active the pupil is not anymore on the lenslet array but the beam orientation is kept in the parallel beam for a given field of view. The beams are only translated in this parallel beam.
The following table give the maximum field (diameter) of view which is unvignetted for different radius of curvature of the membrane mirror

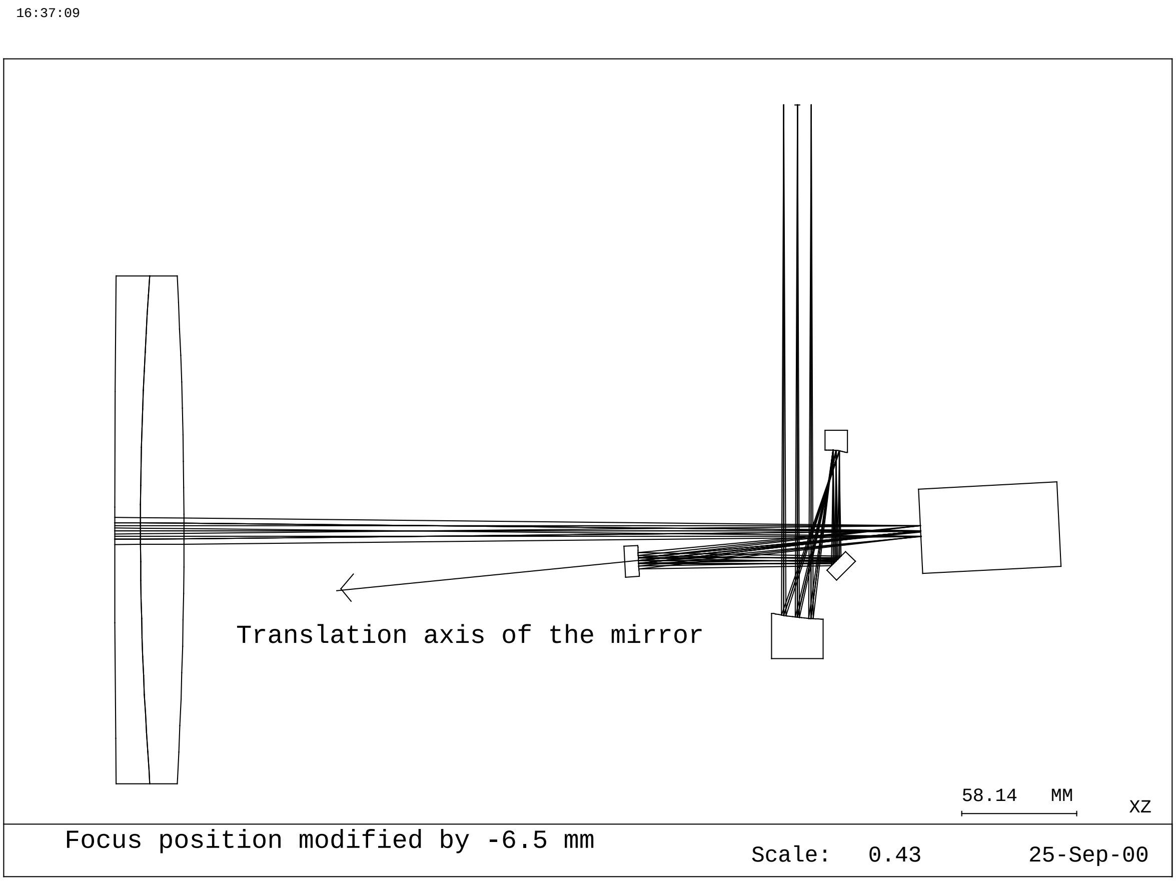
Radius of membrane mirror	Unvignetted field of view
R = ∞	4.4 arcsec*
R = 3000 mm	4.2 arcsec
R = 2000 mm	2.6 arcsec
R = 1000 mm	1.6 arcsec
R = 500 mm	0.8 arcsec

* limited by the diameter of the 2nd lenslet

7 CHANGE OF FOCUS POSITION

MACAO VLTI requires the implementation of an adaptation of the focus position (corresponding to a focus term of 100 nm rms of the wavefront). This value corresponds to +/- 6.5 mm shift of the Focus at the F/46.7 focus.

The membrane mirror will be translated along the wavefront sensor box axis of the incoming beam. The telescope image will be relocated on the centre of the membrane by the XY table. The next figure shows the layout of the system in this new configuration:



The diameter of the beam remains equal to 14 mm on the lenslet array, but the beam is not anymore parallel. The decollimation corresponds to a F/4400 beam. The effect on the light collected by the fibres is negligible.

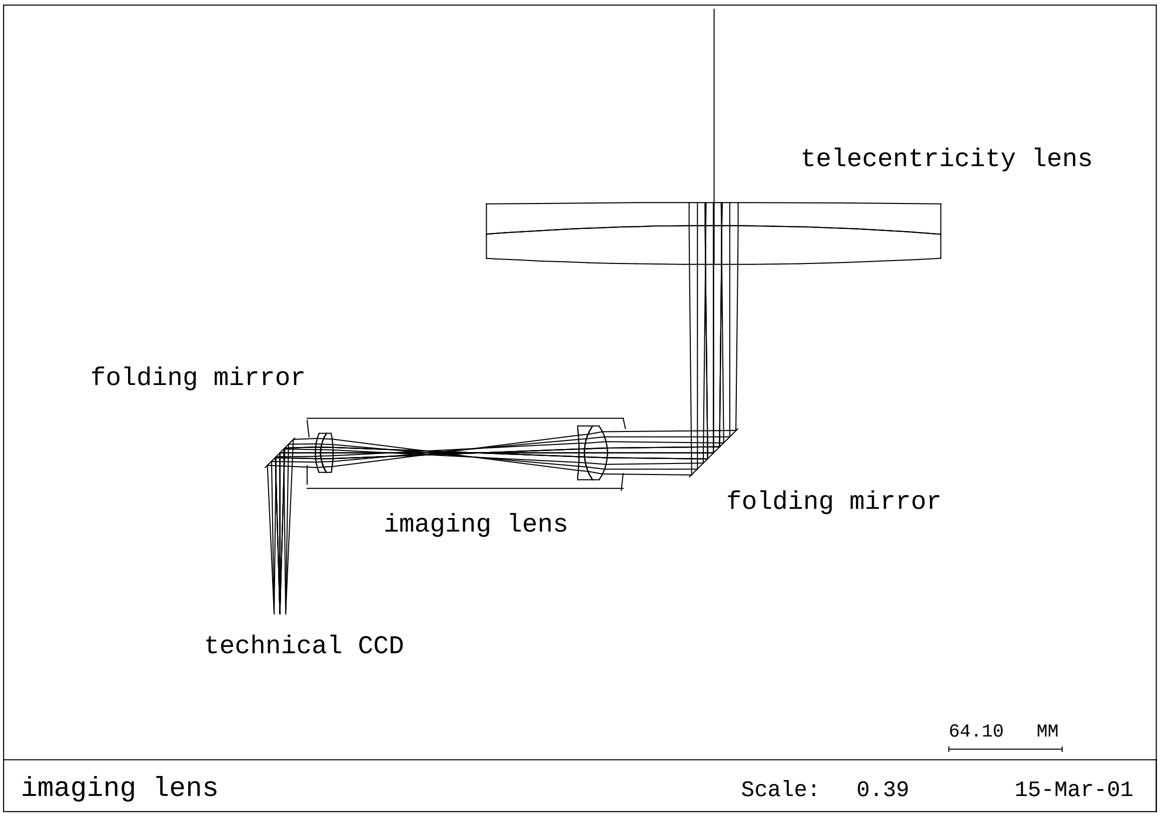
8 THE IMAGING LENS

8.1 INTRODUCTION

The imaging lens is used to image a field of 10 arcsec on a technical CCD. This lens will be located between the telecentricity lens and the wavefront sensor box.
The scale on the CCD is : 1 arcsec = 660 µm

8.2 LAYOUT

10:03:35

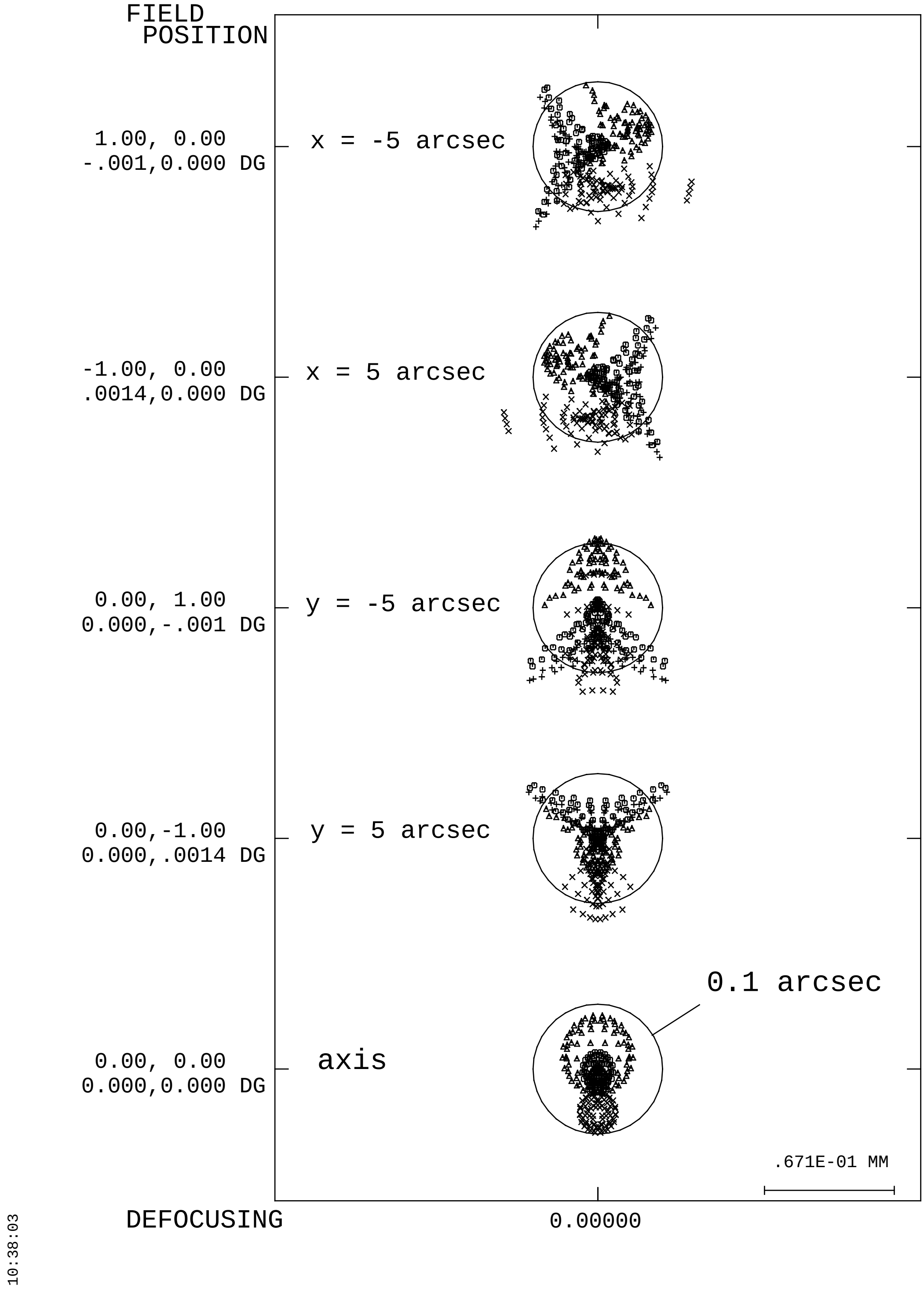


8.3 OPTICAL PRESCIPTIONS

Surface	RAD. of CURV.	THICKNESS	MEDIUM	Free Diameter
Rear surface of telec. lens	-2386.00	106.5	AIR	
Folding mirror	-	-40.0	Refl	
S1	-28.4	-13.0	Ohara SFPL51	26
S2	28.9	-3.0	Ohara SLAL7	26
S3	-159.0	-139.0	AIR	26
S4	-52.6	-7.0	Ohara SFPL51	18
S5	20.0	-3.0	Schott SF4	18
S6	31.0	-20.0	Infinity	18
Folding mirror		91.0	Refl	
CCD	-	-		

8.4 IMAGE QUALITY

The following figure shows a spot diagram of the full system on the CCD. This spot diagram is polychromatic between 450 and 950 nm.


FIELD
POSITION
1.00, 0.00
-.001,0.000 DG
x = -5 arcsec
-1.00, 0.00
.0014,0.000 DG
x = 5 arcsec
0.00, 1.00
0.000,-.001 DG
y = -5 arcsec
0.00,-1.00
0.000,.0014 DG
y = 5 arcsec
0.1 arcsec
0.00, 0.00
0.000,0.000 DG
axis
.671E-01 MM
DEFOCUSING
0.00000
10:38:03