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Optical study of IR PRESSMAGO collector

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Abstract

A feasibility study of an optical system to concentrate and to focalize the synchrotron radiation beam inside the PRESS-MAG-O device has been proposed. This report describes the study two different configurations of the collector system that match the optical and mechanical requirements, obtaining performances in agreement with opto-mechanical constrains. The study analyzes requirements and performances of the collectors for both a collimated and non-collimated configurations of the source. At the end a comparison between performances of the two configurations and short conclusions are given.

PACS.: insert the exact ref. number

1 INTRODUCTION

PRESS-MAG-O is an original device designed to investigate materials under extreme conditions, i.e., as a function of both pressure and DC magnetic field in a wide temperature range [1]. The apparatus has been completely developed at the INFN as the result of a project funded by the Vth Committee of the INFN [2]. Materials like ferroelectrics or superconducting systems, magnetic transitions and new condensed matter phases will be investigated with this device that permits concurrent magnetic and optical experiments. A FTIR spectroscopic analysis in a wide IR domain represents a new strategic approach combining information of the phonon behavior with linear and non-linear electron dynamic transport processes. The apparatus is the result of a significant R&D in different areas. Several technical advancements guaranteed the construction of the cryostat and its internal components thanks also to the availability of new materials and a high level technological processes. The PRESS-MAG-O instrument has been designed to perform FTIR spectroscopy in transmission or reflection modes and Raman spectroscopy experiments.

For IR experiments PRESS-MAG-O will be installed at SINBAD (Synchrotron Infrared Beamline At DAΦNE), the first Italian IR beamline that exploited the great advantages of the synchrotron radiation sources in the IR domain. This beamline is operational at the National Laboratories of Frascati of the INFN since 2001 [4] where a brilliant IR SR source is available. A brilliant IR SR is indeed ideal to perform high-pressure investigations on small samples inside a DAC and this is particularly true at DAΦNE (Double Annular Φ-factory for Nice Experiments), the Frascati electron-positron collider working in topping up mode at an energy of 0.51 GeV per beam with a maximum beam current > 2 A.

SINBAD has been designed to work at IR wavelengths from about 10 cm^{-1} up to 10000 cm^{-1} and operates with a customized BRUKER Equinox 55 interferometer working in vacuum and a BRUKER Hyperion 3000 microscope. Different experiments have been performed a SINBAD using DACs, in particular those on manganite samples at pressures up to 10 GPa. [5].

Actually, the collimated beam coming out from the interferometer and entering the PRESS-MAG-O setup will be focused on the sample loaded inside the DAC by using one of the four lateral ports equipped by optical transmitting windows. Among the many windows that can be installed for optical experiments, a CVD wedged diamond window is the best option to cover the widest range from the visible down to the far-IR domain [3].

A Cassegrain concentrator has been considered and designed to fit the internal dimension of the apparatus. It will focus the synchrotron radiation in a small-size spot, i.e., with a diameter of the Airy disk of ~200 μm at the shortest wavelength, suitable to fit the small size of a diamond anvil cell.

Aim of this work is to describe the optical design to reach the stringent requirements of the PRESS-MAG-O experiment.

2 OPTICAL AND MECHANICAL REQUIREMENTS

The concentrator will have the maximum possible numerical aperture, fulfilling constrains imposed by the small physical dimensions of the pipe in which will be installed. The wavelength range of the collector ranges from the InfraRed to the far-InfraRed, i.e., between 2-20 μm, with the possibility to work down to 50 μm.

The entrance beam diameter is Φ ~ 30 mm and the optical system has to be placed inside a stainless steel cylinder with the optical axis coincident with its axis. At the end an optical window of 16 mm of diameter will be installed. The clear aperture of the window is ~15 cm and the distance between the window and the axis of the magnet (where the focus of the optical system is fixed) is 39 mm. The required spot dimension is 300 μm ± 100 μm.

2.1 Mechanical structure

The stainless steel tube showed in Fig. 1 is divided in two sections. The first is 225 mm long and the second is 325 mm, taking into account also the length of the ceramic break outlined in Fig. 1 with the white colour.

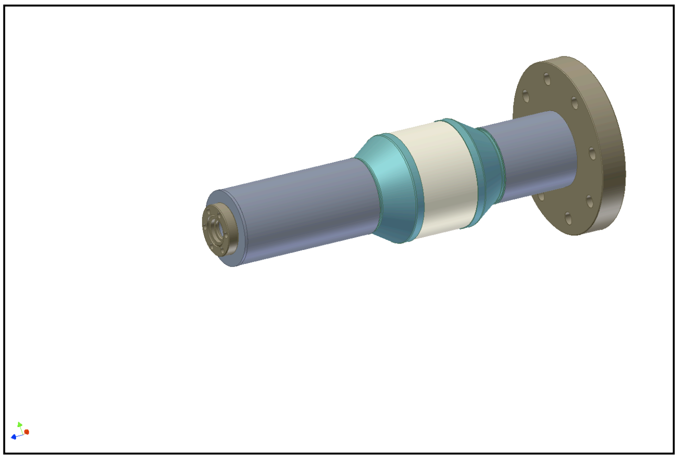


FIG 1 A 3D-view of the stainless steel vacuum pipe and the ceramic break.

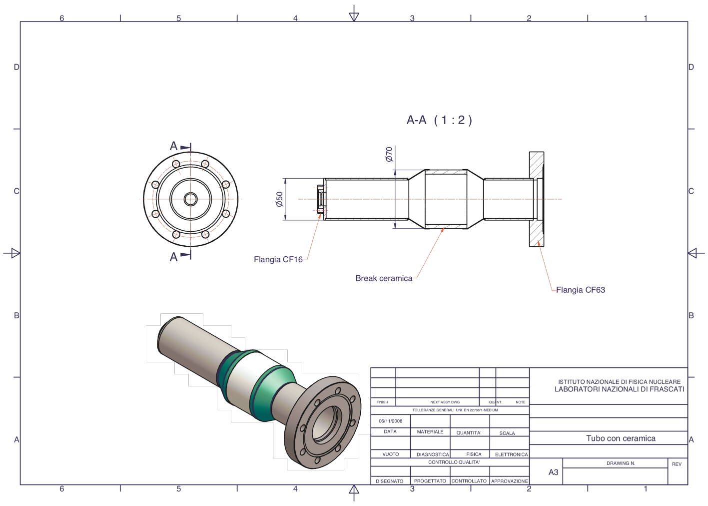


FIG. 2 Mechanical view of the internal pipe of the PRESSMAGO device.

TAB 1: Main parameters of the concentrator

Wavelength range (µm)	2.5-50
Source collimated max. diameter (mm)	40
System length available (mm)	225/325
Window thickness (µm)	500
Window clear aperture diameter (mm)	15
Distance window-target (mm)	39
Optical Tube dimension (mm)	225/325

The main starting conditions of the concentrator are:

- a large wavelength range (2.5-50 µm) that imposes as the solution a reflecting system;
- minimize the total number of mirrors.

This feasibility study shows solutions with the obscuration on axis, i.e., concentrator Cassegrain configurations. For this application where we need to concentrate the light to the target although it may reduce the illuminated area of mirrors, an off axis optic is not an efficient solution.

1. Cassegrain concentrator in a 225 mm long tube

The first optical configuration is a Cassegrain, developed to be set inside an optical pipe that will be inserted in an external steel tube. The mechanical axis of the system has to coincide with the optical axis and its opto-mechanical dimensions are reported in the Table 2. Fig. 3 shows the ray tracing of the optical system for a collimated source.

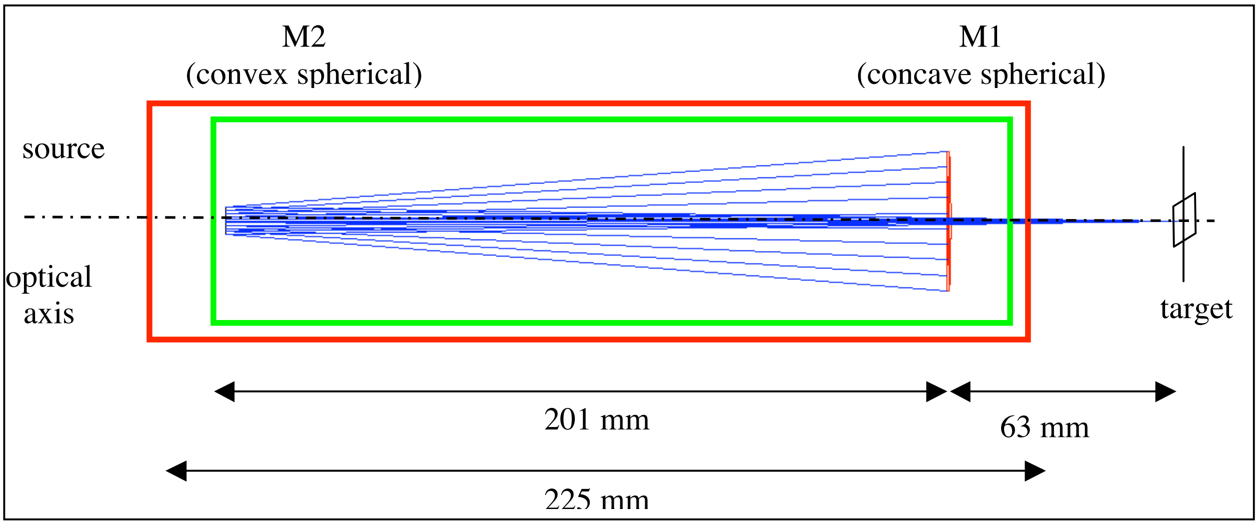


FIG. 3 Layout y, z of the Cassegrain solution with a central obstruction of 3.8%.

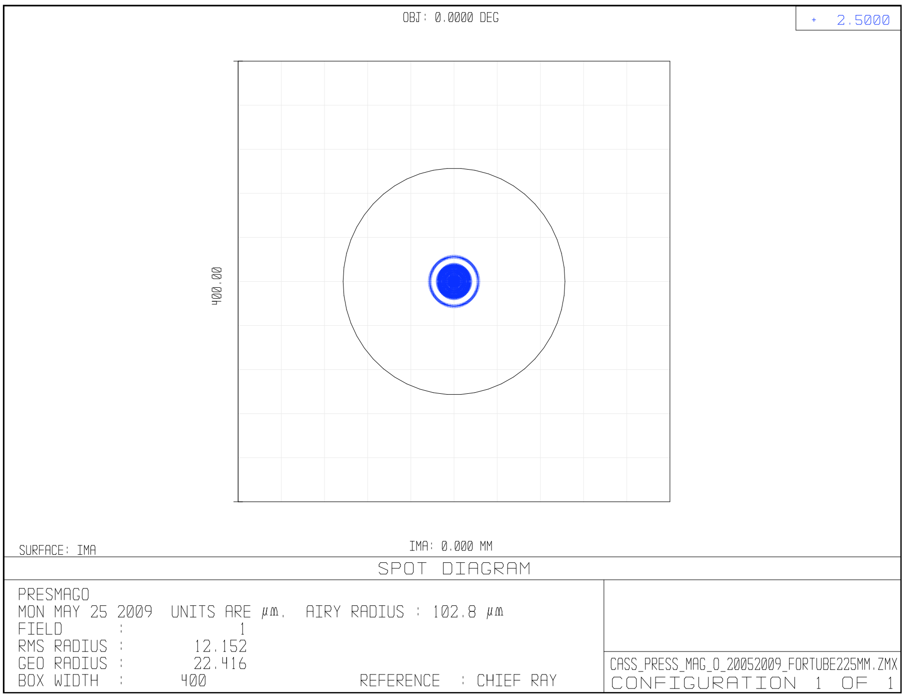
TABLE 2: Optical parameters matching the requirements of the device

f /#	33.7
Diameter Mirror M1 (mm)	40
Thickness Mirror M1 (mm)	6.7
Curvature radius concave M1(mm)	500
Diameter Mirror M2 (mm)	7.8
Thickness Mirror M2 (mm)	1.3
Curvature radius convex M2(mm)	119.94
Distance Window-M2 (mm)	5
Distance Center M1-M2 (mm)	201
Distance Center M2-target (mm)	264.8
Obstruction factor (R_2^2/ R_1^2) %	3.8
Diameter Mirror M1 (mm)	40
Global efficiency (collector) %	86.5

The efficiency of this solution is determined by its performances, the mirrors reflectivity (R=0.95) and by the obstruction coefficient that reduces the source area only by 3.8% (Obs= 0.038). As a consequence the efficiency is

$$Eff= (100-3.8)*0.95*0.95=0.865$$

The Fig. 4 and Fig. 5 show the spot diagram at the wavelength of 2.5 and 20 μm.



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PRESMAGO
MON MAY 25 2009  UNITS ARE µm.  AIRY RADIUS : 102.8 µm
FIELD       :          1
RMS RADIUS  :      12.152
GEO RADIUS  :      22.416
BOX WIDTH   :     400              REFERENCE  : CHIEF RAY
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FIG-4 Spot diagram inside the Airy disk for the central field of the Cassegrain configuration with an Airy disk of 102.8 μm at the wavelength of 2.5 μm.

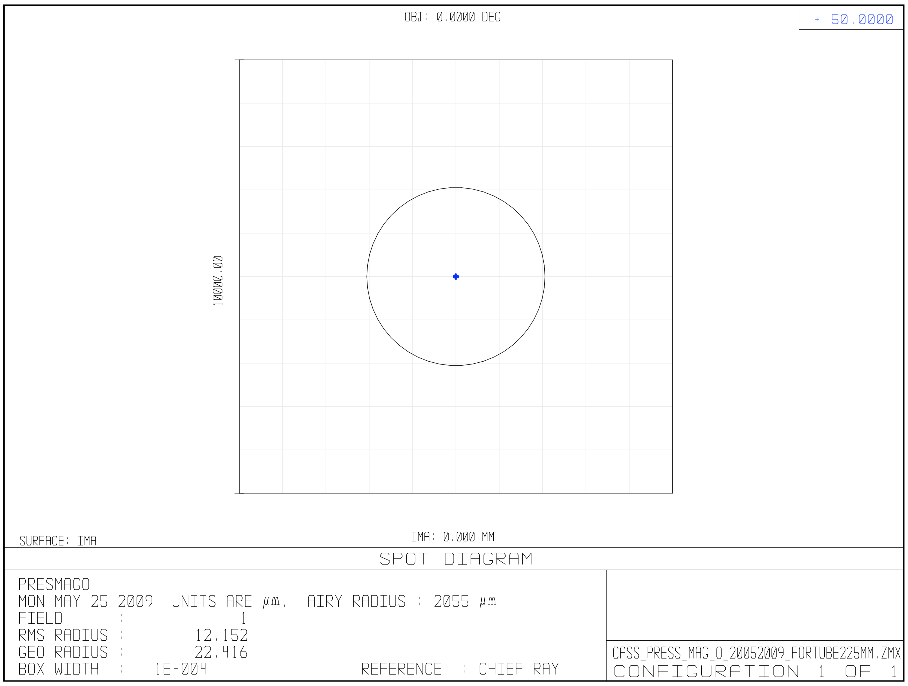


FIG 5 Spot diagram for a collimated source with a Cassegrain configuration with an Airy disk of 2055 µm at the wavelength of 50 µm.

The system is diffraction limited and optically perfect as showed by the spot diagram focus inside the Airy Disk. (It represents the minimum dimension of the image that can be obtained with such optical system).

2. Optical parameters for the mirrors of the PRESSMAGO collector

In Table 3 we report the mechanical tolerances of the optical elements while in Table 4 are summarized the distances. In Fig. 6 are showed the mirrors sections.

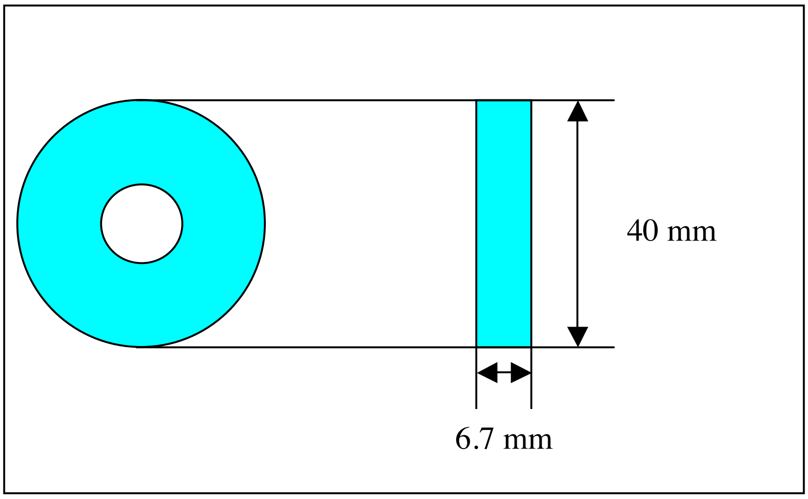
TABLE 3: Optical parameters of the collector mirrors

Mirror Diameter M1 (mm)	40.0 ± 0.2
Mirror Thickness M1 (mm)	6.7 ± 0.2
Curvature radius M1 (mm) concave	500
Mirror Diameter M2 (mm)	7.8 ± 0.2
Mirror Thickness M2 (mm)	1.3 ± 0.2
Curvature radius M2 (mm) convex	119.94

TABLE 4: Mechanical parameters of the collector mirrors

Distance sample-diamond window (mm)	39
Thickness -diamond window (µm)	500
Distance diamond window-external pipe (mm)	2
Distance diamond external tube-internal pipe (mm)	5
Length external pipe (mm)	225
Internal Diameter of external pipe (mm)	48
External diameter of the internal pipe	46
Internal diameter of the internal pipe	44
Length internal pipe (mm)	220
Distance Center M1-M2 (mm)	201
Distance Center M2-target (mm)	264.8
Obstruction factor (R_2^2/R_1^2) %	3.8
Global efficiency (collector) %	86.5

Concave mirror M1 (R=500 mm)



Convex mirror M2 (R=119.94 mm)

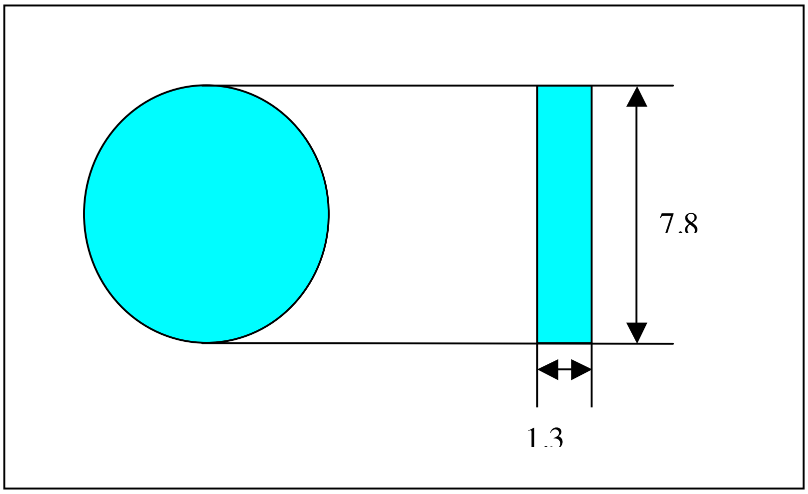


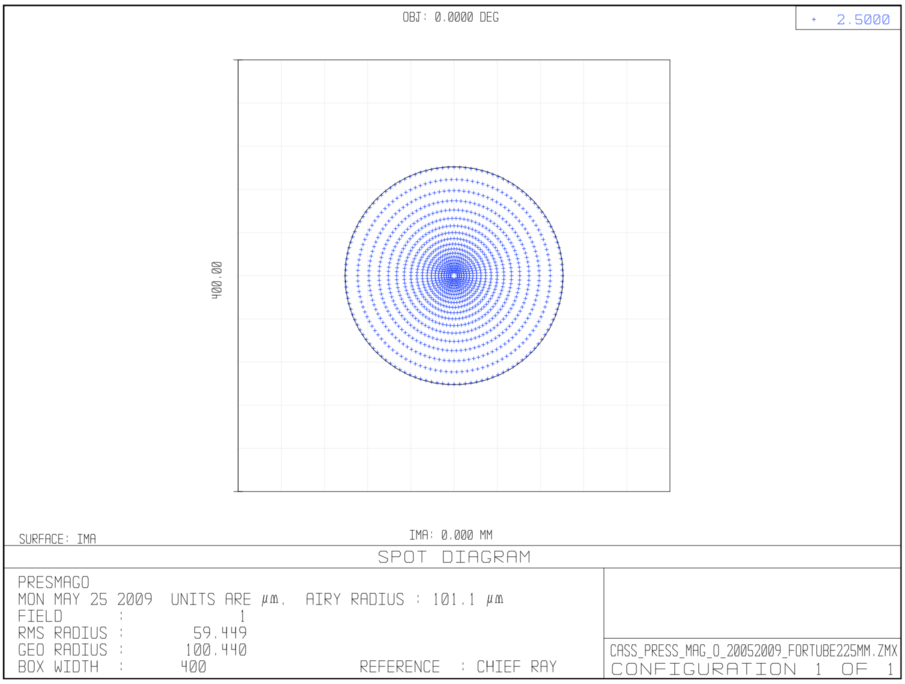
FIG. 6 Mechanical layouts of the primary and the secondary mirrors.

3. Sensitivity analysis

The sensitivity analysis is a procedure that allows evaluating the mechanical tolerances on inter-distances and tilts maintaining focus and optical axis. The analysis allows establishing among all the more sensitive optical element, e.g., curvature radius or distances, changing the different optical parameters of defined quantities still fulfilling the diffraction limit constrains. Table 5 shows mechanical tolerances required to remain diffraction limited while Fig. 7 shows the image of the spot diagram obtained changing the inter-distance between the primary and the secondary mirror.

TABLE 5: Mechanical tolerances of the optics still remaining diffraction limited.

Sensitivity budget for baseline						
Surface	**Radius (mm) TOL**		**Thickness (mm) TOL**		**Decenter (mm) shift center spot ± 200 µm**	**Tilts_xy shift center spot ± 200 µm**
Primary concave mirror	-500	-0.6 +0.35	-201	-0.18 +0.25	±0.037	-0.010°
Secondary Convex mirror	-119.9	-0.5 +0.9	264.8	-5 +8	±0.045	±0.035°



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PRESMAGO
MON MAY 25 2009  UNITS ARE µm.  AIRY RADIUS : 101.1 µm
FIELD      :          1
RMS RADIUS :     59.449
GEO RADIUS :    100.440
BOX WIDTH  :    400                REFERENCE  : CHIEF RAY
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FIG 7 Spot diagram diameter of a collimated source obtained translating the secondary mirror by 180 µm respect to the primary mirror.

Data obtained with our sensitivity analysis showed that the most sensitive elements are:

- M1 for both curvature radius and tilt (0.010°, 1.75 mrad)
- Distance M1-M2 (-0.18, +0.25 mm)
- Defocusing (± 5 mm)

To evaluate tolerances with non-collimated rays, the source divergence simulation has been modified and the distance of the focus has been calculated.

▪ 0.1 mrad (to be diffraction limited)	defocusing 1 cm (to refocus)
▪ 1 mrad (no diffraction limited)	defocusing 19 cm (to refocus)

4. Concentrator Cassegrain in a 325 mm of tube

The second Cassegrain configuration to be set inside an optical tube and inserted in the external stainless steel pipe of Fig.1 has been also analyzed. In Fig. 8 we show the ray tracing obtained for a collimated source. Also in this configuration the mechanical axis has to coincide with the optical axis and its opto-mechanical dimensions are reported in Table 6. The opto-mechanical dimensions are also reported in Table 6.

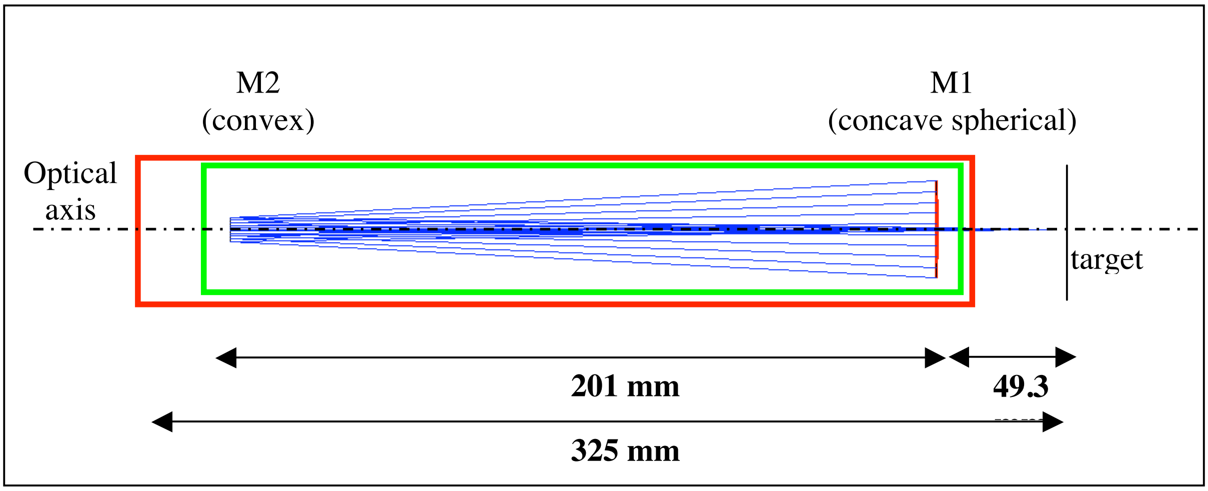


FIG 8 Layout y, z of the Cassegrain solution with a 4% of central obstruction.

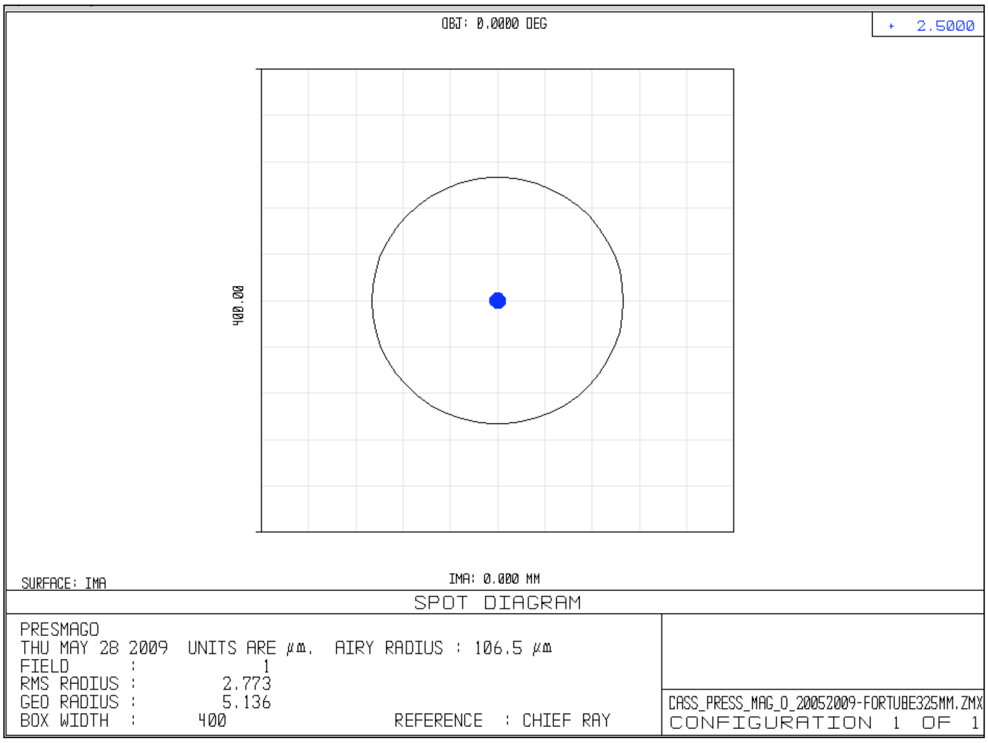
The efficiency of this solution in determined its performances, the mirrors reflectivity (R=0.95) and by the obstruction coefficient that reduce the source area by 4% (Obs= 0.04).

$$\mathrm{Eff}= (100-4)*0.95*0.95=0.866$$

The Fig. 9 and Fig. 10 show the spot diagram of this configuration at the wavelength of 2.5 and 20 µm.

TABLE 6: Optical parameters matching the requirements of the device

f /#	35
Diameter Mirror M1 (mm)	40
Thickness Mirror M1 (mm)	6.7
Curvature radius concave M1(mm)	800
Diameter Mirror M2 (mm)	5.0
Thickness Mirror M2 (mm)	0.83
Curvature radius convex M2(mm)	280
Distance Window-M2 (mm)	5
Distance Center M1-M2 (mm)	300
Distance Center M2-target (mm)	349.3
Obstruction factor (R_2^2/ R_1^2) %	4%
Global efficiency (collector) %	86.6



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PRESMAGO
THU MAY 28 2009  UNITS ARE µm.  AIRY RADIUS : 106.5 µm
FIELD       :            1
RMS RADIUS  :        2.773
GEO RADIUS  :        5.136
BOX WIDTH   :      400                REFERENCE  : CHIEF RAY
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CASS_PRESS_MAG_0_20052009-FORTUBE325MM.ZMX
CONFIGURATION  1  OF  1
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FIG 9 Spot diagram inside the Airy disk for the central field of a Cassegrain solution with 106.5 µm of Airy disk at the wavelength of 2.5 µm.

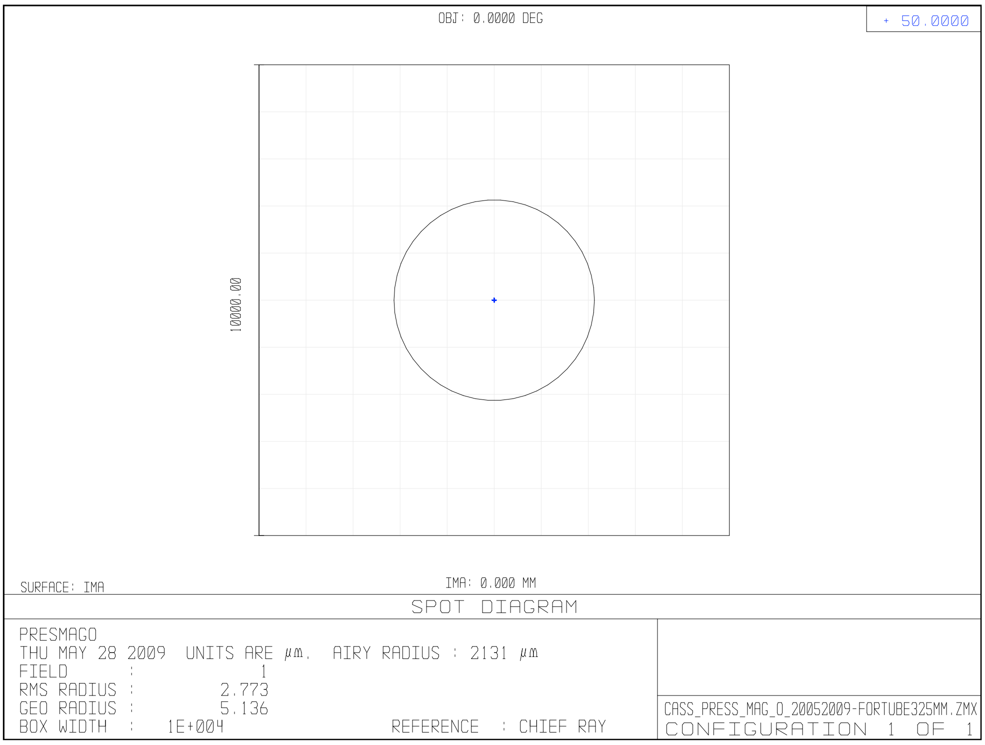


FIG 10 Spot diagram for a collimated source and a Cassegrain solution with 2131 µm of Airy disk at the wavelength of 50 µm.

Also in this configuration the system is diffraction limited and optically perfect as the spot diagram inside the Airy Disk clearly shows. (It represents the minimum dimension of the image that can be obtained with the optical system).

5. Optical parameters for the mirror collector of PRESSMAGO

Table 7 shows the mechanical tolerances of the optical elements while Table 8 the distances of the system. Fig. 6 shows the section of the mirrors.

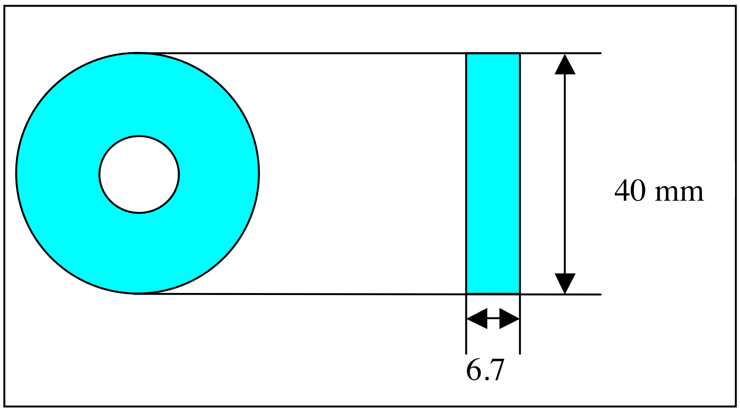
TAB 7: Optical parameters of collector mirrors

Mirror Diameter M1 (mm)	40.0 ± 0.2
Mirror Thickness M1 (mm)	6.7 ± 0.2
Curvature radius M1(mm) concave	800
Mirror Diameter M2 (mm)	5.0 ± 0.2
Mirror Thickness M2 (mm)	0.8 ± 0.2
Curvature radius M2 (mm) convex	240

TAB 8: Mechanical parameters of collector mirrors

Distance sample-diamond window (mm)	39
Thickness -diamond window (μm)	500
Distance diamond window-external pipe (mm)	2
Distance diamond external tube-internal pipe (mm)	5
Length external pipe (mm)	325
Internal Diameter of external pipe (mm)	48
External diameter of internal pipe	46
Internal diameter of internal pipe	44
Length internal pipe (mm)	320
Distance Center M1-M2 (mm)	300
Distance Center M2-target (mm)	349.3
Obstruction factor (R_2^2/ R_1^2) %	4
Global efficiency (collector) %	86.4

Concave mirror M1 (R=800 mm)



Convex mirror M2 (R=240 mm)

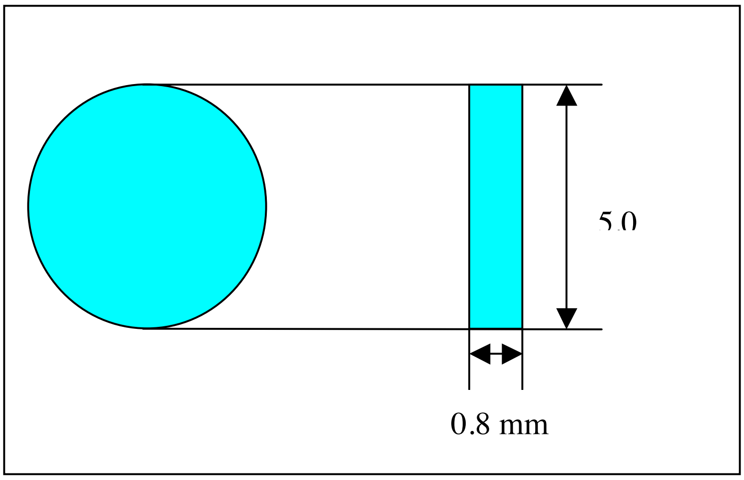


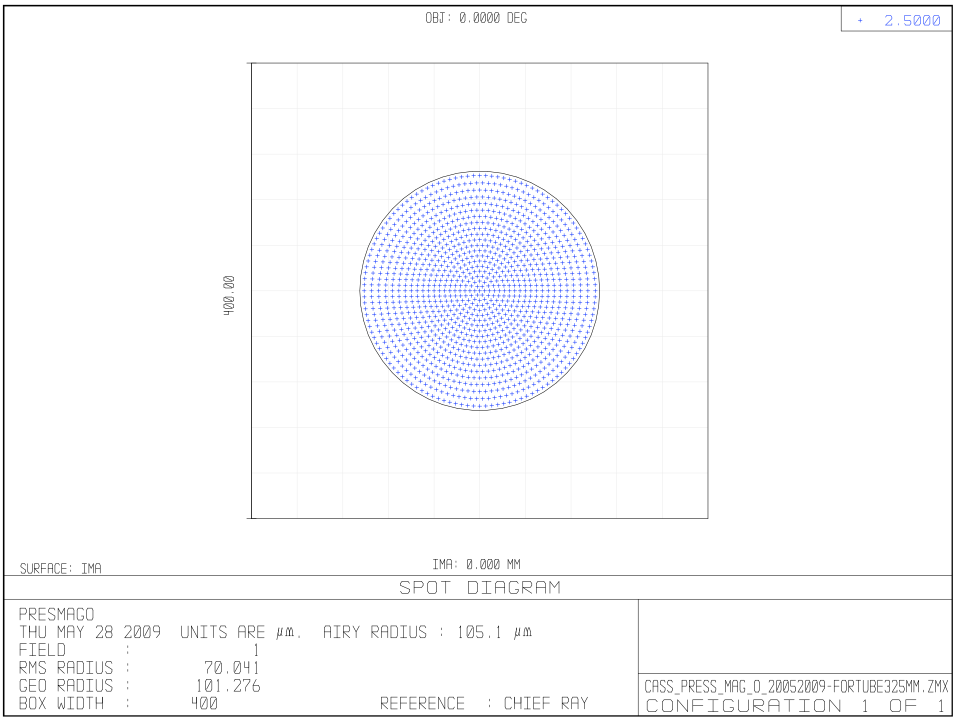
FIG 11 Mechanical layouts of primary and secondary mirrors.

6. Sensitivity analysis

The sensitivity analysis here reported is the same defined in the section 3.

TAB 9: Mechanical tolerances of the optics still remaining diffraction limited.

Sensitivity budget for baseline						
Surface	**Radius (mm) TOL**		**Thickness (mm) TOL**		**Decenter (mm) shift center spot ± 200 µm**	**Tilts_xy shift center spot ± 200 µm**
Primary concave mirror	-800	-1.3 +1.1	-300	-0.55 +0.65	±0.058	±0.0065°
Secondary Convex mirror	-280	-2.0 +2.4	-349.3	-7 +7.5	±0.080	±0.030°



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PRESMAGO
THU MAY 28 2009  UNITS ARE µm.  AIRY RADIUS : 105.1 µm
FIELD       :          1
RMS RADIUS  :     70.041
GEO RADIUS  :    101.276
BOX WIDTH   :    400                 REFERENCE  : CHIEF RAY
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CASS_PRESS_MAG_0_20052009-FORTUBE325MM.ZMX
CONFIGURATION 1 OF 1
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FIG 12 Spot diagram of a diameter collimated source obtained translating the second mirror by 550 µm respect to the first fixed mirror.

Data obtained with the sensitivity analysis show that the most sensitive elements are:

- M1 for both curvature radius and tilt (0.11 mrad=0.0065°)
- The distance M1-M2 (-0.55, +0.65 mm)
- The defocusing (± 7 mm)

Tolerances for non-collimated rays are:

- 0.16 mrad (to be diffraction limited)   defocusing 1.5 cm (to refocus)
- 1 mrad (no diffraction limit)   defocusing 17 cm (to refocus)

7. Comparison

The two optical systems are optically equivalent, both are diffraction limited and reach the main optical design requirements. The radiation is focused on ~100 µm of the Airy Disk and it is contained in ~300 µm as required.
In Tab. 10 a tolerance comparisons is schematically summarized.

TAB 10: Sensitivity and tolerances data of the optical systems analyzed

Sensitivity		
	System 225 mm	**System 325 mm**
Tolerance in a collimated rays		
Mirror M1 tilt (deg)	0.010° (1.75 mrad)	0.0065° (0.11 mrad)
Distance M1-M2 (mm)	-0.18, +0.25	-0.55, +0.65
Refocusing (mm)	± 5	± 7
Tolerances with non collimated rays		
Source divergence limit with a diffraction limited system (mrad)	0.1	0.16
Refocusing (mm)	10	15
Source divergence limit with not diffraction limited system (mrad)	1	1
Refocusing (mm)	190	170

8. Conclusions

The feasibility study for a real optical system to concentrate and to focalize a synchrotron radiation beam and match it with the PRESS-MAG-O instrument has been investigated. This report describes the study of a collector with two different configurations, taking into account both optical and mechanical requirements. Results show that ideal performances are in agreement with the opto-mechanical constrains.
The study demonstrates that both systems we considerate can be compliant with the optical requirements. As a consequence the final solution has to be chosen on the base of mechanical constrains, such as an easier alignment procedure or the introduction in the vacuum pipe. In particular for the second configuration a simpler positioning and alignment procedure is foreseen due its mechanical constrains.

9. Acknowledgements

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10. References

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