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Final correction by Ion Beam Figuring of thin shells for X-ray telescopes

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ABSTRACT

Future space X-ray mission concepts like STAR-X, AXIS and Lynx foresee optics with both high angular resolutions (HEW ~ 0.5 to 5 arcsec) and large collecting areas (~0.2-2.0 m^2). These optics are very challenging to be produced and their manufacturing is under study. The Ion Beam Figuring (IBF) is one of the few techniques that is capable of correcting the residual manufacturing errors of the mirror shells and obtain the desired final optical figure. INAF-OA-Brera has two IBF facilities and is investigating the use of IBF on thin foils made by different materials, namely Silicon and Fused Silica. In this paper we describe the results obtained in a preliminary study on Silicon shells.

Keywords: Lynx, STAR-X, X-ray optics, thin shells, Ion Beam Figuring

1. INTRODUCTION

Present day studies of space X-ray missions to be launched in the next decades (e.g. STAR-X[1], AXIS[2], and Lynx[3]) foresee optics with angular resolutions up to 0.5 arcsec HEW and collecting areas up to 2 m^2 at 1 keV. These technical requirements will probe for the first time the assembly of black holes and of large scale structures in the early Universe. As an example, the STAR-X mission concept aims at performing wide-and-deep X-ray surveys at 5 arcsec resolution or better over hundreds to thousands of deg^2 of sky. This will allow the discovery of millions of AGN, including hundreds at z>6-7, and several thousands of galaxy clusters, including a few hundreds at z>1.5. A stable PSF over a large, ~1 deg^2, field of view will be the key to perform such effective surveys, which, remarkably, will match in area and sensitivity those performed in the future by Euclid[4], LSST[5], SKA1[6].

The optics of these X-ray telescopes are very challenging to be produced and technologies employing Silicon optics have been proposed and studied mainly in USA by the NASA Goddard Space Flight Center[7] (GSFC). The Ion Beam Figuring (IBF), a non-contact process, is probably the best technique to correct the shells by smoothing the surface errors left by other polishing techniques to the required final optical figure. Tests using the IBF technique have been done recently at the GSFC with promising results[8]. At the Astronomical Observatory of Brera (INAF-OA-Brera) we started a two years project, financed by the Italian Space Agency (ASI), aiming at using the IBF on very thin Silicon shells. To this end, we started with two representative Silicon mirrors provided by the GSFC in the frame of a mutual collaboration. Here, we report on the results obtained on these mirrors figured with the IBF.

1.1. The Ion Beam Figuring technique

The Ion Beam Figuring uses a beam of Argon ions to remove material from an optical surface by means of kinetic impact. They are accelerated by a suitable potential difference between the grids of the source (generally a Kaufmann type) and hit the surface at a typical distance of about 10 cm from the grids. By keeping constant the power of the source and moving the beam with a variable speed, a different amount of material is removed to correct the residual errors on the optical surface. Before using the IBF process, it is necessary to characterize the shape and removal rate of the beam in order to obtain the so-called removal function (RF). This is done with a static run in which an interferometrically measured flat sample, of the same material of the optic to be corrected, is placed in the beam for a definite amount of time, generally 10-20 min, creating a depression in the sample. The sample is then measured deriving the amount of material removed (see Fig. 1). This RF has a symmetric shape similar to a Gaussian, and is usually expressed in terms or

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the removed material thickness per unit time, for example nm/sec. From this RF and from the map of the errors of the surface it is possible to compute how long the Ion Beam needs to stay on each pixel of the optical surface to remove the desired amount of material. For the tests performed in this study, with the electrical setup shown in Table. 1, the removal rate obtained in the Gaussian peak on the Silicon was of 4.5 nm/sec and the overall size of the RF was 28mm with a FWHM of 9mm.

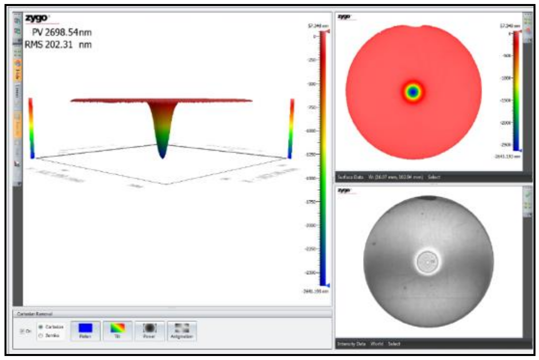

Fig. 1 Interferometric measure of the “hole” created on a 100 mm Silicon sample made to obtain the RF (10 min exposure)

Beam Current	Beam Voltage	Accelerator Voltage	Beam Power
5 mA	750 V	100 V	3.75 W

Tab. 1 RF main electrical parameters

1.2. The Ion Beam Facility

For this initial test we have used the large facility[9] available in our Institute and shown in the auto explicative Fig. 2

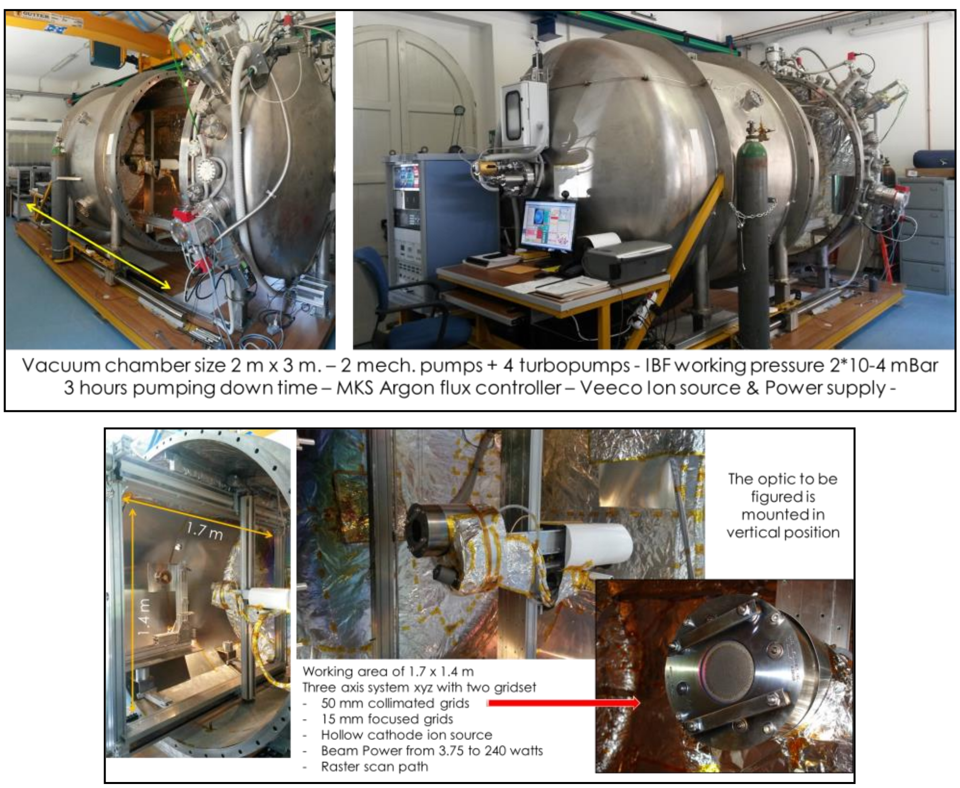

Fig. 2 Characteristics of the large IBF facility in INAF-OA-Brera

A second smaller facility, able to figure optics up to 300 mm in diameter, is also available (Fig. 3) and is presently under refurbishment and it will be used for the follow-up of this study since the size of the X-ray shells to be investigated is well within its capability and the system is much more practical than the larger one.

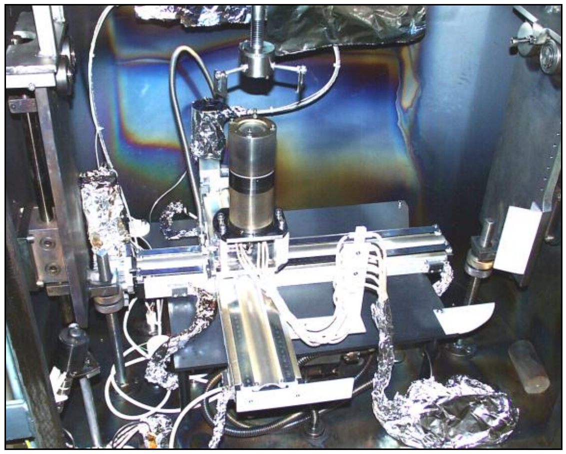

Fig.. 3 IBF facility for optics up to 300 mm

2. THE THERMAL LOAD AND THE SHELL MOUNT

Even if Silicon is essentially a material free of stresses, care must be taken to avoid depositing an excessive thermal load on it. In fact, the IBF is a process in which the Argon ions are accelerated and hit the surface removing material and depositing a relative large quantity of energy. To mitigate the heating, that also depends on the Beam Power used and can bring the substrate temperature up to 80-90 °C, the shells have been mounted on an aluminum curved block (Fig. 4) fixed on the holder, that keeps the samples in a vertical position during the figuring (Fig. 5 ,6). The shells are thermally interfaced with the aluminum block using a temperature resistant vacuum grease from Apiezon. Three small holding fingers made by graphite were used to ensure that the Silicon shells were well fixed and stable. It has been monitored that during the figuring the temperature of the aluminum block reached a peak of 37 °C, a low temperature that guarantees very low thermal stresses on the shells.

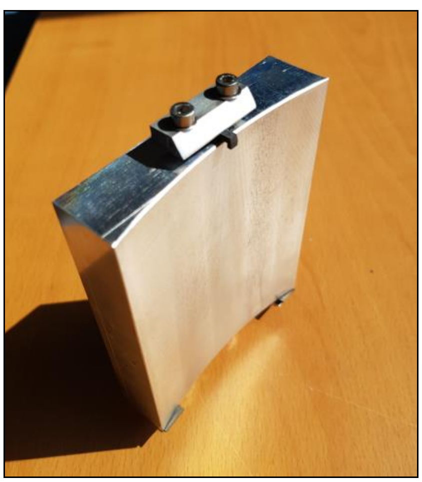

Fig.. 4 Curved Al block

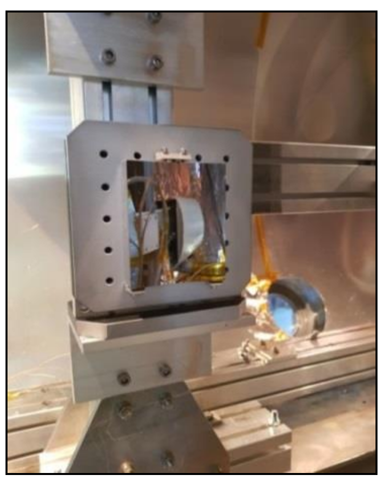

Fig. 5. Holder with the Al block

Fig.. 6 Top view

The two mirrors have a radius at the P-H intersection of about 156.2 mm and hence this was chosen as the value for the curved surface of the Al block, with the small dimensional differences accommodated by the grease. The focal length of the combined pair mirrors is of 8400 mm. They are Wolter-I, parabola and hyperbola mirrors.

3. ION BEAM FIGURING OF THE PRIMARY MIRROR

3.1. Characteristics of the 312P1052 sample

This sample is the Parabola component of the two mirrors provided by GSFC. It is made by a mono-crystalline Silicon component having dimensions of 80x100 mm, 1.22 mm thick and with a weight of 23.6 g.

3.2. IBF result on 312P1052 sample

The map of the surface with the errors was provided by GSFC and was loaded into the software for the Time Matrix computation (Fig. 7).

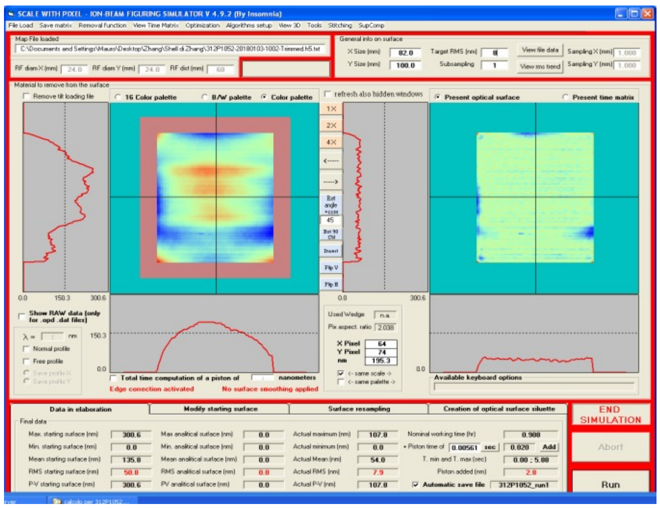

Fig. 7 Computation of the Time Matrix

The figuring time obtained was of 0.9 hours. Fig. 8 shows the surface before and after the figuring. In these data a 2nd order Chebyshev Coefficient has been removed. A convergence factor of 3.5 was obtained (defined as the ratio of the rms before and after the IBF). The rms decreased from 32 to 9 nm rms. The improvement in the overall figure of the mirror is clearly visible after the figuring. The axial geometric RMS slope error, excluding the second order, was reduced from 1.3 arcsec to 0.56 arcsec.

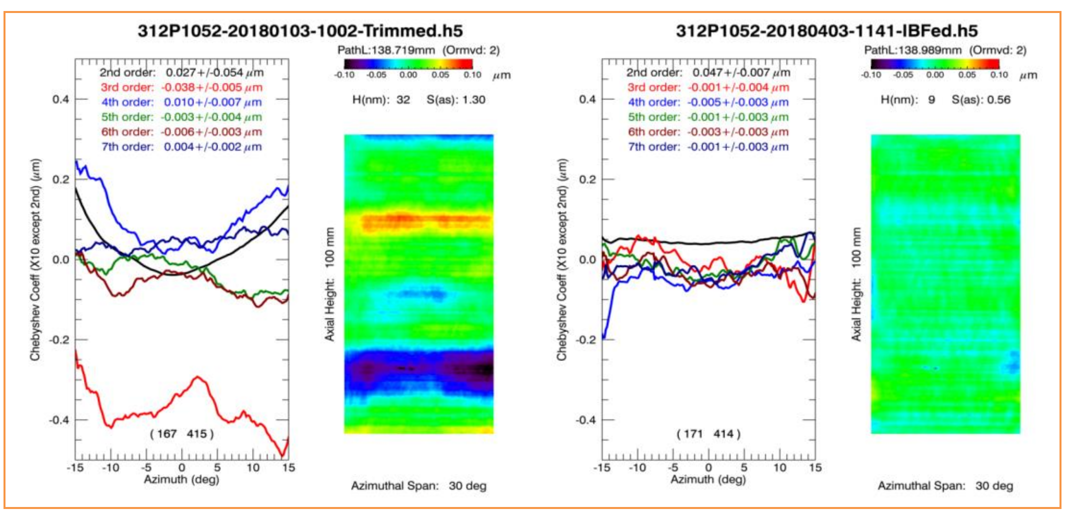

Fig. 8 Sample 312P1052 before and after the figuring

3.3. The 312P1052 sample PSD before and after IBF

The PSD of the 312P1052 sample is shown in Fig. 9. The improvement for spatial scales larger than 9 mm, i.e. the FWHM of the removal function, is clearly visible. At smaller scales, the PSD behavior is essentially unchanged, as expected.

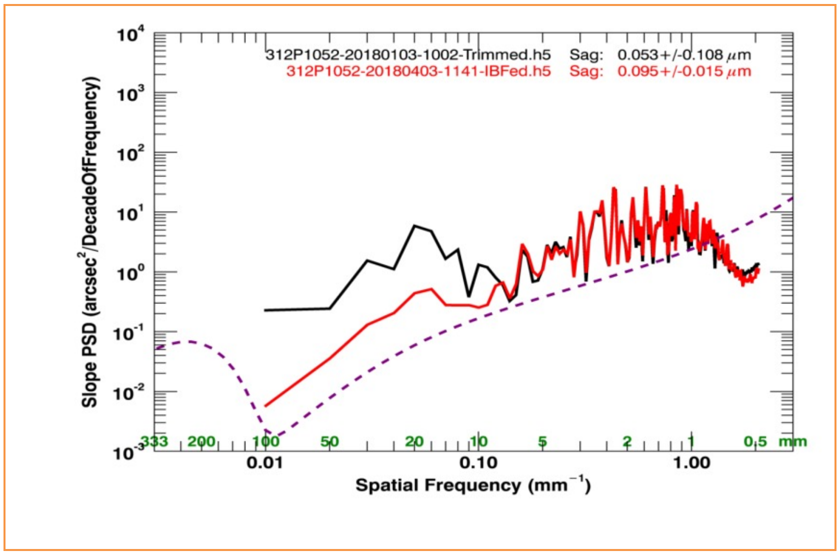

Fig. 9 The red line shows the improvement in PSD

4. ION BEAM FIGURING OF THE SECONDARY MIRROR

4.1. Characteristics of the 312S1024 sample

This sample is the Hyperbola component and it is made by a mono-crystalline Silicon component having dimensions of 80x100 mm, 0.76 mm thick and with a weight of 14.6 g.

4.2. IBF result on 312S1024 sample

The map of the surface with the errors was loaded into the software for the Time Matrix computation (Fig. 10).

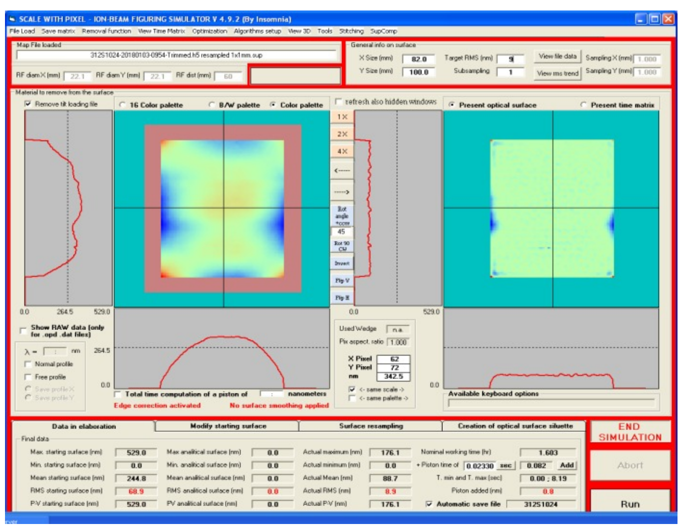

Fig. 10 Computation of the Time Matrix

In this case, the figuring time obtained was of 1.6 hours. In Fig. 11 is shown the surface before and after the figuring. Also in these data the 2nd order Chebyshev Coefficient has been removed. In this case the rms decreased from 28 to 7 nm rms with a convergence factor of 4. The improvement in the overall figure of the mirror after the figuring is clearly visible. The axial geometric RMS slope error, excluding the second order, was reduced from 0.83 arcsec to 0.57 arcsec.

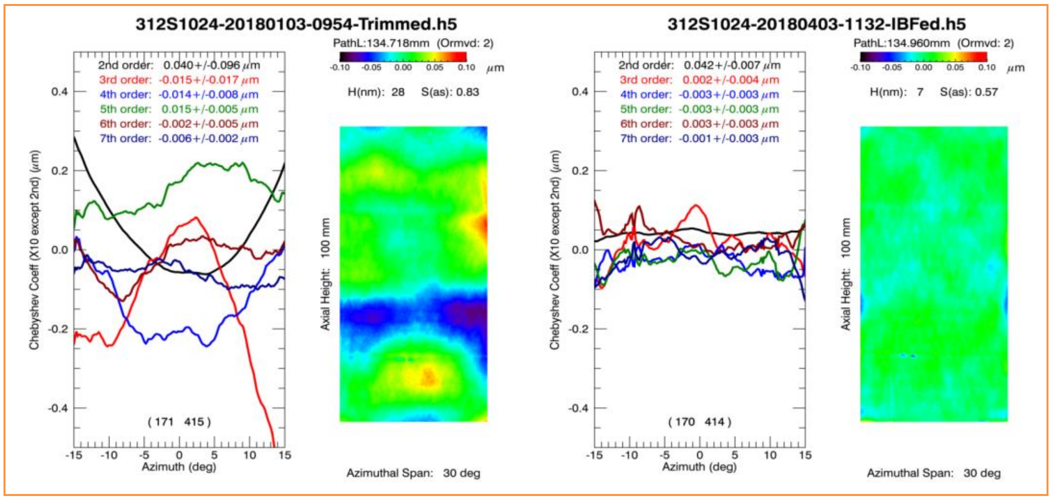

Fig. 11 Sample 312S1024 before and after the figuring

4.3. The 312S1024 sample PSD before and after IBF

The PSD of the sample 312S1024 is shown in Fig. 12. Similarly to the previous sample, the high frequencies / small scales are essentially unchanged. The improvement on scales longer than 9 mm is instead clearly visible.

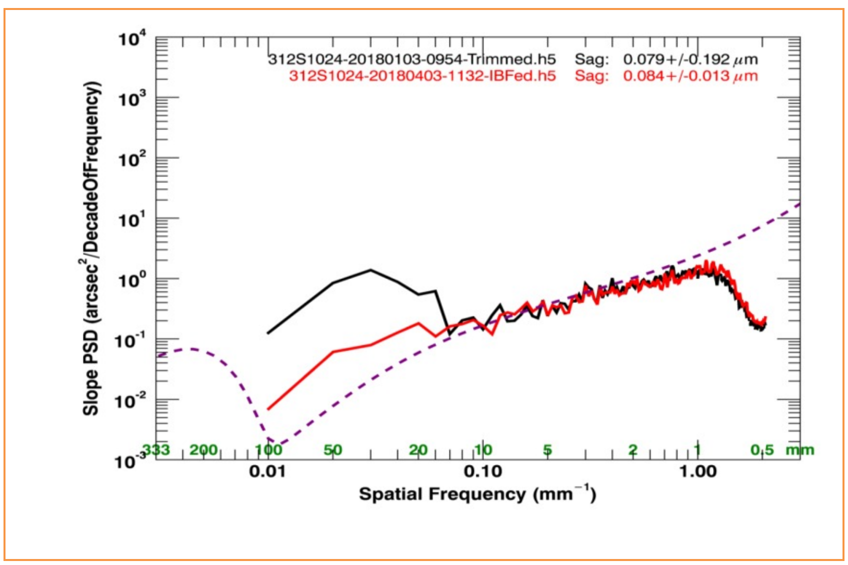

Fig. 12 The red line shows the improvement in PSD

5. CONSIDERATIONS ON MIRROR DEVELOPMENT

For the two Silicon mirrors figured in this initial experiment, we estimated that, if properly aligned, they would produce images with ~1.5" HEW at 1 keV. The initial image quality of the pair was estimated to be ~3" HEW. A second IBF run (not performed) could have further improved the final HEW. The IBF improved by a factor of 3.5-4 the rms height error at low spatial frequencies (length scale > 10 mm). One of the aims of this study is to increase this "convergence factor" (the ratio between the initial rms and the final rms of the surface) in order to fully correct a segment in a single IBF run. A full correction in a single IBF run is a key achievement to speed up the production process, due to the large numbers of shells necessary to the construction of an X-ray telescope.

After the figuring and metrology of the samples, the sagittal depth of the mirrors (accounting for null lens calibration) are:

- Expected: 98 nm.
- Sample 312P1052: (95 +/- 14) nm.
- Sample 312S1024: (84 +/- 14) nm.
- Combined sag error: 17 nm → 0.27" HEW.

The mid-to-high-frequency errors (spatial scales shorter that 9 mm) did not change at all, as expected. The PSD for spatial scales longer than 9 mm instead have improved.

Moreover, the micro-roughness of the surfaces is consistent with no changes after the figuring, even if there is some indication of a small re-deposition of material on the shell surfaces. This effect will be investigated and if necessary mitigation strategies will be implemented.

6. CONCLUSIONS

The correction of two X-ray Silicon mirrors using Ion Beam Figuring has shown the great potential that this technique has for the final correction of the X-ray optics of future X-ray missions like STAR-X and Lynx.
A collaboration of two years with NASA GSFC has just started in the frame of an ASI financial contribution. Single mirror prototypes produced by GSFC will be sent to OA-Brera and will be figured through Ion-Beam Figuring. The single crystal mirrors are developed by GSFC using the direct polishing approach that provided already very promising results (3 couples of segments integrated and measured in X-ray, with an angular resolution of 3.6 arcsec HEW). Since the main residual error is due to low frequency errors (a few cm of spatial wavelength) a significant improvement can be obtained via Ion Figuring. Preliminary tests performed at both GSFC and OA-Brera have shown very promising results, with the possibility to bring the residual error to just a fraction of arcsec. Using the ion figuring facilities already available, OA-Brera will correct a number of Si substrate samples. They will be integrated into a Wolter I mirror assembly, aiming at measuring sub-arcsec angular resolution in the X-rays. During this study 6 couples of super-polished Silicon mirrors will be corrected with Ion Beam Figuring and X-ray calibrated in collaboration with GSFC.

In parallel, as a spare technology, we will continue the development of fused silica substrates that are also giving promising results.

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