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Ion beam figuring of thin glass plates: achievements and perspectives

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ABSTRACT

Different hot slumping techniques have been developed in the last decade to shape thin glass plates in Wolter-I configuration for high angular resolution x-ray telescopes. The required high quality surface characteristic, both in terms of figure error and of micro-roughness, is challenging and the best results achieved so far are compatible with an HEW of few arcseconds. In order to push forward the technology enabling x-ray optics with final HEW below 1 arcsec, we investigate the ion beam figuring as a deterministic technology which can correct the low frequency components of the residual error directly on thin glasses.

In this paper we present the tests performed so far, giving a first assessment on the deterministic process definition. In particular, we report on the results achieved on flat samples of D263 and Eagle glass, focusing on the removal function characterization, the micro-roughness evolution and the plate shape variation.

Keywords: X-ray grazing-incidence telescopes, ion beam figuring, X-ray segmented mirrors, hot slumping, thickness variation, deterministic correction

1 INTRODUCTION

In the last decade, different hot slumping techniques have been developed to shape thin glass plates in Wolter-I configuration for high angular resolution x-ray telescopes. In order to limit the weight of the mirrors, the required thickness of these substrates is very small, typically around 0.4 mm. Different glass materials, like AF32, D263 and Eagle, have been studied by different groups [1,2,3,4,5]. The best results achieved so far are compatible with an HEW of few arcsec. Given the thickness of the samples, the implementation of further corrections is a difficult task. A non-contact and deterministic figuring technology like the ion beam figuring may be the solution to correct the residual error on thin glass foils. This final figuring could push forward the technology and make them adapted to high throughput x-ray optics with final HEW below 1 arcsec. Due to the required high quality surface characteristic, both in terms of figure error and in micro-roughness, different aspects should be evaluated in this final process definition. The work started on flat samples and in this paper we present the results of preliminary tests. In particular, we report on the results achieved on flat samples of D263 and Eagle glasses, chosen because available in our laboratories as already in use for the hot slumping tests. We performed the removal function on D263 and Eagle using our ion beam figuring facility: both the removal rate and the micro-roughness has been characterized. Once measured the Gaussian shaped removal function, we have set a pattern and the stock of material to be removed, and we have tested it on different samples of glasses. The comparison between the measurement of thickness acquired before and after the figuring has been used to validate the effectiveness of the process is terms of removal. On the other side, the measurement of the figure error on the glass plate provides indication on the deformation the surfaces may suffer under exposure to the ion beam. The different experimental set-ups used to characterize the micro-roughness, the thickness variation and the figure error are presented in paragraph 2. The removal function characterization and the measurement of the micro-roughness before and after figuring process are presented in paragraph 3. The ion beam figuring test results on the different materials are presented in paragraph 4.

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2 MEASUREMENT SET-UP

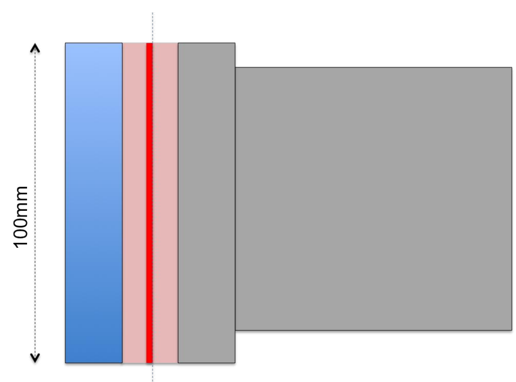
In order to characterize the ion beam process on thin glass plates, different kind of measurements have been performed. For the micro-roughness characterization, the Micro-Finishing-Topographer [6] has been used. With the available 10x objective, it maps the surface on the 1mm scale. This is one of the most critical wavelength ranges for x-rays mirrors with incidence angles around 0.7°. Thanks to its limited weight the instrument can be placed above the sample to be measured.

With a thickness of 0.4mm, the measurement of the figure errors for the glass plate is not simple and two different approaches have been used. First, we have evaluated the amount of material removed by measuring the thickness variations with an interferometric set-up. Second, we have measured the shape of the optical surface of the glass with a non-contact optical profilometer.

The thickness variations on the thin glasses have been measured with the Zygo interferometer. A flat reference in BK7 (Optosigma) with 100mm diameter was used in reflection to close the optical cavity. The Zygo residual map has an rms value of 66.9nm, with a PtV of 243.52nm. Since the flat reference is common to all the measurements acquired before and after the ion beam figuring, its intrinsic shape error is negligible as soon as differential values are considered. This is the case of the thickness variation measurements: the sample is placed in between the interferometer flat reference and the external flat reference. The different optical path experienced by the laser beam is only related to the different glass thickness. The interferometer laser beam has a diameter of 100mm, therefore, for greater areas, a stitching procedure has been adopted. In these cases, reference markers have been drawn on the glass by means of a mask. Errors in the results can be related to the misalignments of the data acquired before and after the run of ion beam figuring.

For the deterministic correction tests, the flat glass samples have been cut to the size adopted in segmented x-ray mirrors. The size is 127mm x 200mm and we have used the same metrological set-up to compare the shape of the glass samples before and after the ion beam figuring. The metrology has been carried out with the Characterization Universal Profilometer (CUP) [7], with the glass placed in vertical position with two supporting points on the bottom (61mm distance) and one on the backside. The measurement configuration has been simulated with FEMs: the preliminary results (for 0.4mm D263 glass) show that the measurement is repeatable within 100nm if the position of the supporting points is repeatable with respect to the vertical direction within 82micron, when the backside support is at 50mm from the top edge of the glass. The amplitude of the deformation (PtV) introduced by gravity is 1/1000 of the inclination used for the measurement: with 2mm displacement over 200mm length, the expected PtV is 2micron. In figure 1 are reported the measurement schemes for the thickness variation and for the 3d figure errors characterization. The corresponding realized measurements set-up are shown in figure 2.

Slices of 300mm x 120mm have been cut out of the original 300mmx300mm glass foil to characterize the ion beam removal function, in terms of depth of removal and effect on the glass micro-roughness.



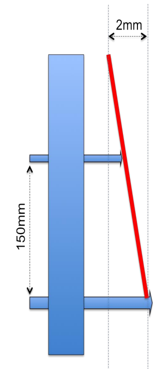


Figure 1: (A) The interferometric measurement set-up: the interferometer is colored in grey, the glass in red and the flat reference used to close the cavity (light red) is in blue. (B) The vertical set-up of the glass plates during the 3D measure with the CUP.

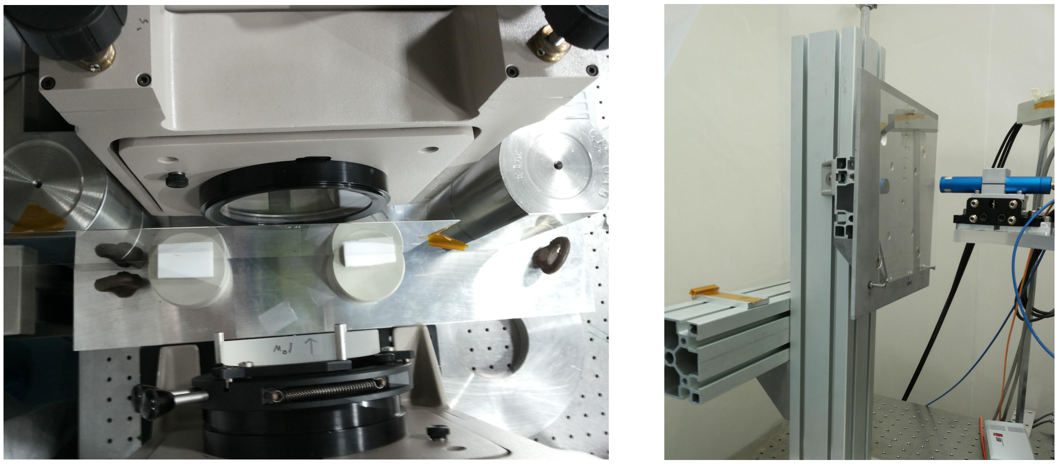


Figure 2: (A) Measurement set-up for glass thickness variation. 100 mm diameter BK7 reference mold used to close the cavity. (B) 3d measurement of plates figure errors.

3 REMOVAL FUNCTION CHARACTERIZATION

The ion beam figuring tests have been carried out with the large facility available at INAF/OAB. The system has been completed in 2013 and enables a large working area (1.7 m in width and 1.4 m in height). The facility has seen its "first light" by figuring a 1m optical part, in the framework of an investigation on the ion beam figuring of segments for the E-ELT [8,9]. As the movement of the ion source is in a vertical plane, the optics to be figured must be placed and mounted vertically in front of the source. The ion source can travel along three Cartesian axes allowing keeping constant the distance from the optical surface in the case of curved optics (the maximum sag is 60mm). The water-cooled ion source is provided with two graphite grid sets having different sizes: a 50 mm grid set and a 15 mm grid set, that can be used for corrections of long/short spatial wavelengths errors. The power of the beam can be regulated from 6 to 240 watts depending on the requested removal rate.

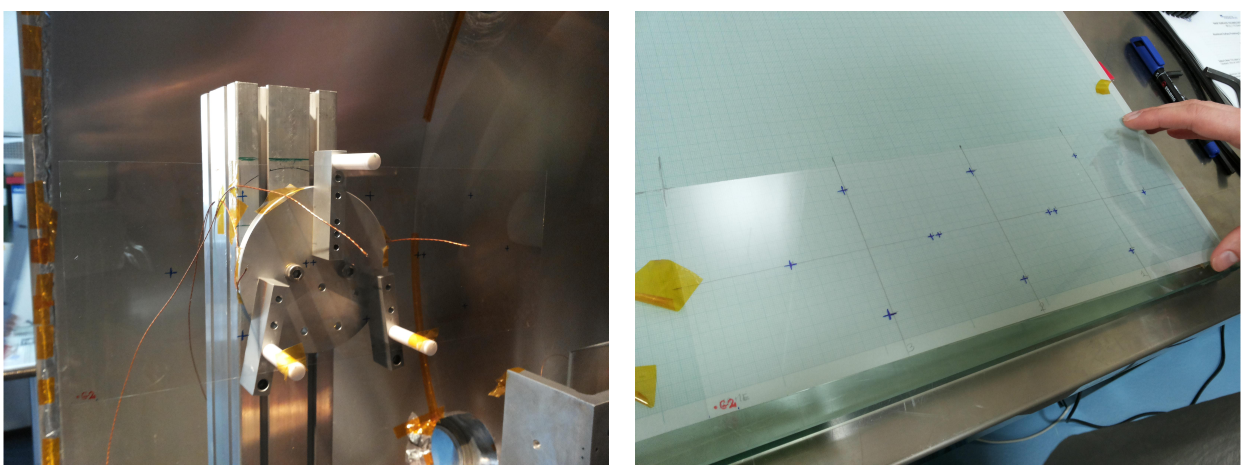


Figure 3: (A) Ion beam chamber configuration for the determination of the removal function. For the G2 sample (D263 glass) thermocouples were applied on the backside of the glass. (B) One of the samples used for the characterization of the removal function. The markers on the back of the glass were used for alignment purpose both in the ion figuring and in the metrology session.

The removal function has been characterized on flat 0.4mm thick samples (one made of D263 and the other of Eagle). For each sample, three removal functions have been produced in three different positions by changing the duration of the figuring (10min, 20min and 30min). Thermocouples have been placed on the backside of the glasses in order to monitor the temperature. In figure 3B the glass sample mounted in the ion beam figuring chamber is shown. In these first tests on thin glasses, the ion source has been operated at 5W, using the 15mm grid set.
For each of three positions, an interferometric map characterizing the thickness variation has been acquired before the figuring. A set of markers has been used to guarantee the correct matching to the interferometric maps acquired after the ion beam figuring (figure 3A). In figure 4 the map before and after the removal function is reported for one of the positions. The amount of material removed changes with the time of figuring, and ranges from around 900nm PtV to around 4micron PtV depending also on the type of glass. The derived values for the removal rates and the Full Width Half Maximum (FWHM) for the two glasses are reported in table 1. The removal rate for the D263 is higher (peak value around 2nm/sec) than the one measured on the Eagle (peak value around 1.5nm/sec) but with a lower repeatability both in terms of amount of material removed and of FWHM.

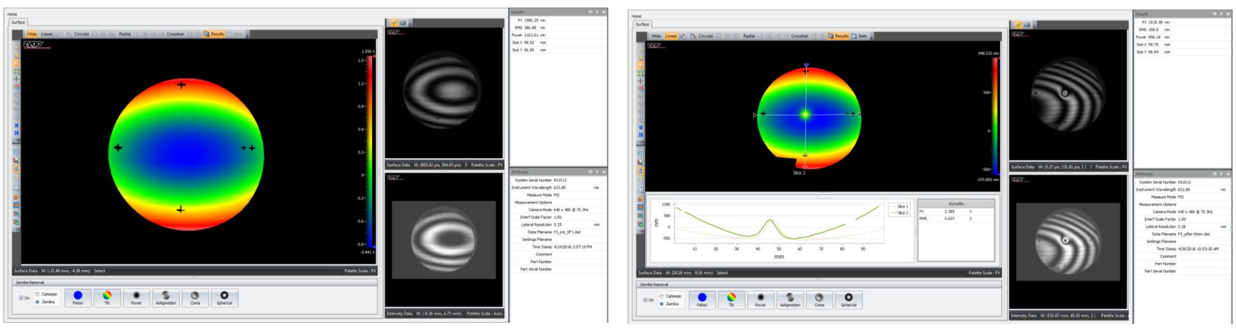


Figure 4: The interferometric maps of the thickness variation acquired for one of the position before and after the removal function figuring.

		Eagle			D263	
	Max. Removed material (nm)	Peak Removal rate (nm/sec)	FWHM (mm)	Max. Removed material (nm)	Peak Removal rate (nm/sec)	FWHM (mm)
10min	910	1.517	8.3	1280	2.133	7.7
20min	1820	1.448	8.4	2435	2.029	8.2
30min	2593	1.441	8.4	3967	2.054	8.5

Table 1: Removal function minimum deep, removal rate and FWHM for the three removal functions figured on the D263 and on the Eagle samples.

For each of the positions figured, the micro-roughness of the surface has been measured before and after the process is order to monitor its evolution: a degradation of the micro-roughness could be a potential showstopper for the ion beam figuring process as a final polishing step of the 'optical' surface of x-ray optics.
In these first trials we focused on the millimeter scale, acquired with the MFT with 10x objective. The measures have been taken in the central position of each of the figured areas. As the amount of the removed material scales with the figuring time in three fixed positions, it was possible to check if it has an impact on the final micro-roughness.
The initial measured maps and Power Spectral Density (PSD) are compared in the top panels of figure 5 for D263. The three maps correspond to the three different positions where different amounts of removed material (1.3micron, 2.4micron and 4micron) have been removed: the corresponding results after the figuring is reported in the bottom panels of figure 5. The measured sigmas are around 0.5nm in all the positions before the figuring. The results are unchanged with the figuring. Furthermore, a smoothing effect is observed in all the position at higher frequencies. As maximum PtV of the removed material is more than 4micron, that is clearly well above the amount of material to be removed for a final ion beam figuring process. This is a clear indication that the micro-roughness evolution is not an issue, at least on the millimeter scale.

The same type of results has been observed on the Eagle sample. The corresponding measured maps and PSD are reported in figure 6. As for the D263 case, the top panels figure refers to the initial measurement on the glass sample in the three positions, while the bottom panels show the situation after the removal of different amount of material (0.9micron, 1.8micron and 2.6micron respectively).
The lack of degradation of the micro-roughness on both the glass types is encouraging: the figuring process can be applied on both the glass materials.

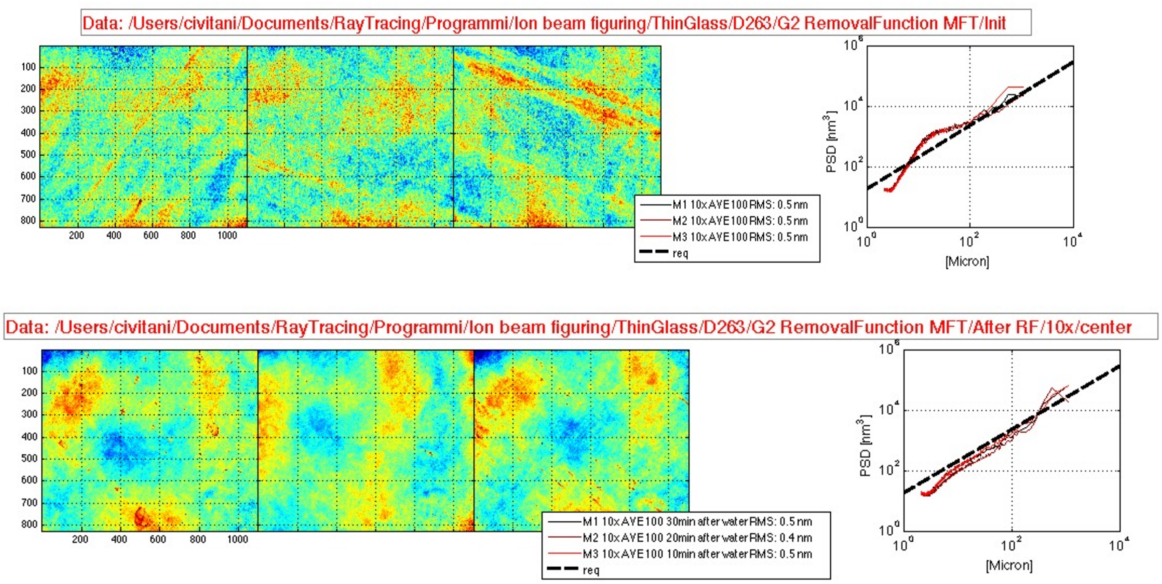


Figure 5: Micro-roughness on around 1mmx1mm area of D263 sample before/after the removal function figuring: (10x MFT maps)

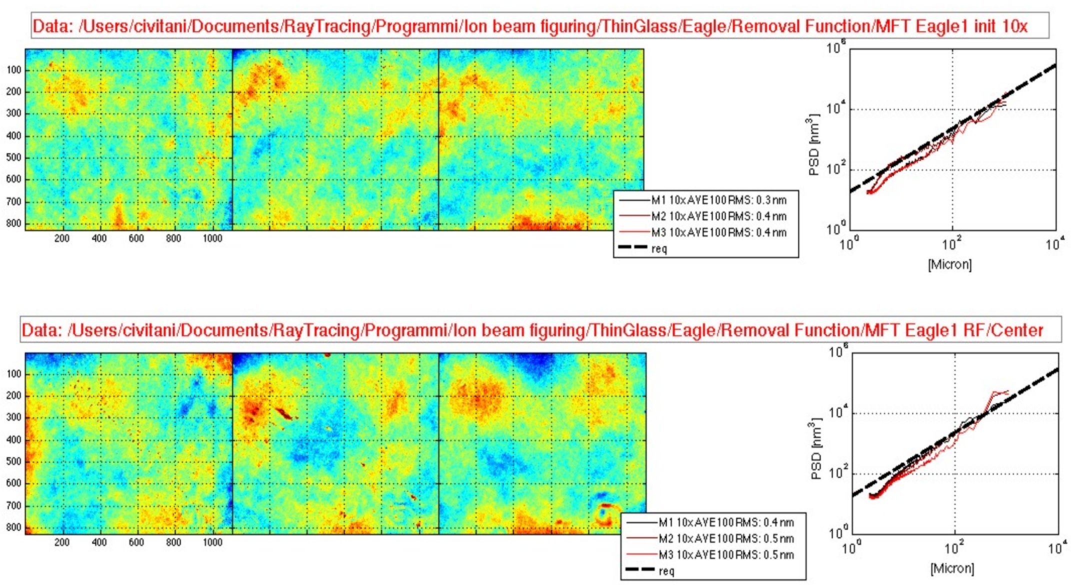


Figure 6: Micro-roughness on around 1mmx1mm area of Eagle sample before/after the removal function figuring: (10x MFT maps)

4 FLAT SAMPLES FIGURING

Once acquired the removal function to be used for the figuring, a corrective map has been defined to figure the glass samples. A symmetric pattern with a maximum PtV of 500nm has been drawn with the shape of a crab. The pattern to be machined is reported on the left side of figure 7. On the right side of figure 7, the result in terms of thickness variation is shown on the D263 sample. Given the size of the glass and the interferometry set-up available, patches of different circular maps have been stitched together to cover the full area. Some defects coming from the non-ideal stitching are clearly visible in the final map and probably concur to the differences from the expected map. Since the stitching error can contribute to the low frequency errors, different sample size will need to be considered in the next planned tests, to avoid these metrological artefacts. This is the first trial showing that the correction of the glass thickness variations is feasible and can be made without any particular constrains. By increasing the FWHM of the removal function we could reduce the figuring time speeding up the process.

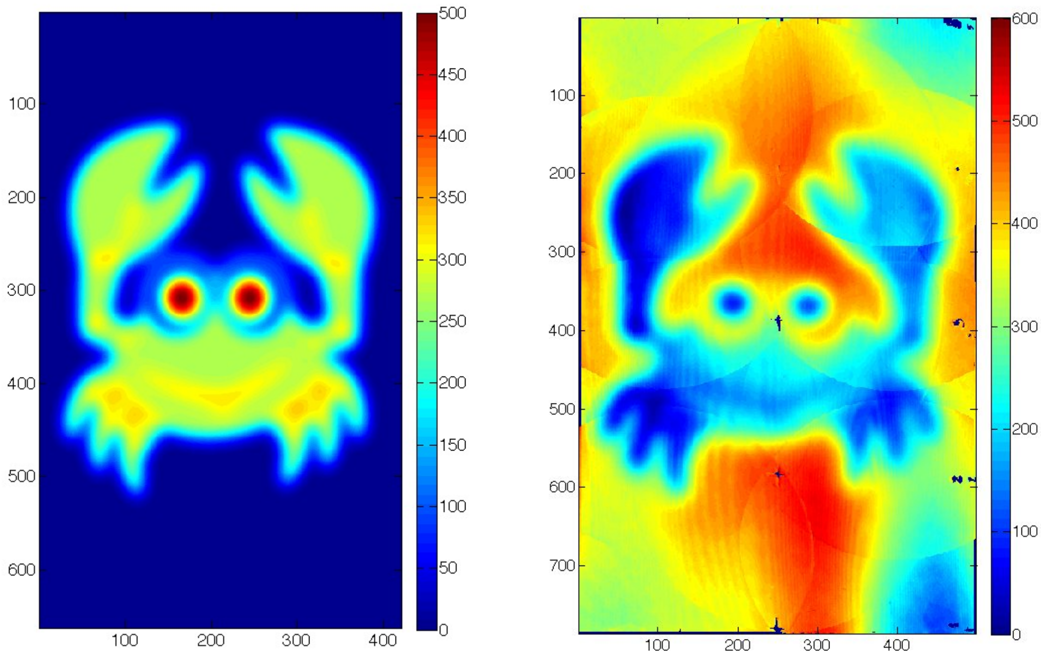


Figure 7: (A) The theoretical corrective map used for the figuring. (B) The measured thickness variations derived as stitching of several interferometry maps.

3D measurements of the thin glass plates have been acquired by means of the CUP. The characterization of the figure error before and after the figuring is crucial to highlight if the ion beam figuring process introduces deformations in the substrates. In figure 8 and 9 the results obtained for D263 and Eagle are reported, respectively. In all the cases, two points on the bottom and one on the top are used to support the glass. The measurement has been repeated several times to check for the repeatability. In the case of the D263 sample, the measurement before the figuring has been repeated two times, before and after the repositioning the sample. For each positioning of glass plate, the measurement has been repeated three times without moving the sample. The glass sample was not flat, with a PtV error of 166.9 $\pm$ 0.7 micron on the overall shape. The repeatability of the PtV for the measurement is of few microns. The measurements acquired after the figuring show a different residual shape with a PtV of 529.4 $\pm$ 4.2microns. These deformations are well above the repeatability limits. The reason for this deformation is still under investigation. It can be related to stress accumulated in the glass during the process. In this case two possibilities are envisaged. An annealing process could be used to release such stress. Another option is to apply ion beam figuring onto the other face of the glass. By removing a constant amount of material, could help to compensate the stress introduced with the first figuring. Both options are still under evaluation.

The situation is different for the case of Eagle glass sample. The measurement has been repeated twice before the figuring and three times after it, repositioning each time the sample. As in the case of D263, the top panels of figure 9 reports the overall deviation from a flat surface, while on the bottom panel it is reported the deviation along the longitudinal axis of the glass. The color scale in this case is 300microns in both the cases. The overall PtV of the residual error from a flat is 293.3 micron before the ion beam figuring while it is 314.1microns after. This variation is compatible with the measurement error experienced in the last measurements. Due to a problem occurred in the power supply of the SIOS unit mounted on the CUP, the latest acquired measurements are strongly affected by noise. This noise turns out in the azimuthal pattern visible in all the maps acquired on the Eagle sample after the figuring. We are confident to achieve results more reliable once the instrument will be repaired.

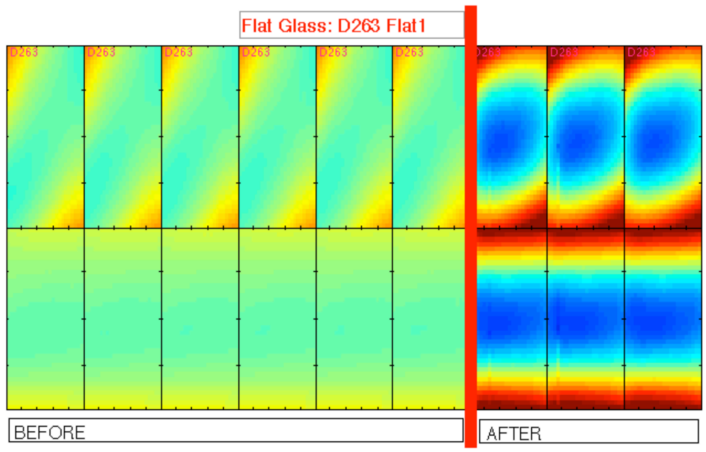


Figure 8: Measured figure error of the D263 sample. The first 6 columns report data acquired before the ion beam figuring, while the last three columns the data acquired after the crab figuring. Top panels show the overall residua on the glass (colorscale is 500 micron), while bottom panels report the longitudinal error profiles. (colorscale is 400 microns). For D263 the overall shape of the glass is changed by more than 350micron PTV (much more of any expected repeatability error of the set-up): the process stresses the glass or the process releases the intrinsic stress of the glass.

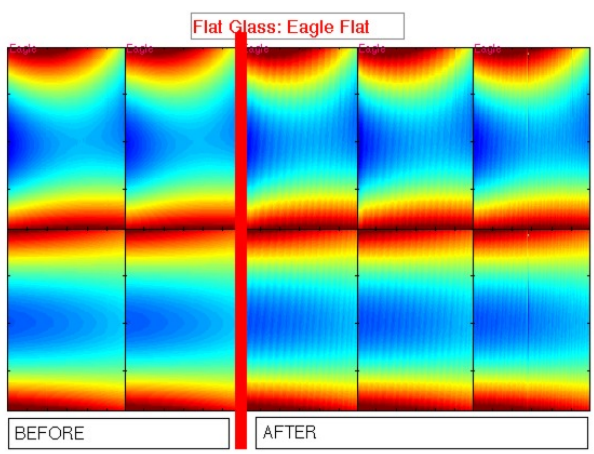


Figure 9: Measured figure error of the D263 sample. The first 6 columns report data acquired before the ion beam figuring, while the last three columns the data acquired after the crab figuring. Top panels show the overall residua on the glass (colorscale is 300 micron PtV), while bottom panels reports the longitudinal error profiles. (colorscale is 300microns PtV). For Eagle glass, the overall shape seems unchanged, but due to an instrument measurement problem only an upper limit of few microns can be set.

5 CONCLUSIONS

In this work, we have tested the ion beam figuring technique on very thin glass plates. Samples of two different materials (Eagle from Corning and D263 from Schott) and thickness of 0.4mm have been chosen. This is the typical thickness of substrates dedicated to light weighted x-ray optics that can be produced via hot slumping process. Different hot slumping techniques have been studied in the last decade to shape thin glass plates in Wolter-I configuration. The best results achieved so far are compatible with an HEW of few arcsec. The aim of this work is to assess the ion beam figuring as a final step in the production chain of thin glass plates. As this is a deterministic and non-contact technique, it could permit the fabrication of x-ray optics with final HEW below 1 arcsec. In the present work, several glass samples of different size and shape were processed by ion beam without breaking. The micro-roughness has been characterized on the millimetre scale and we have observed that it does not degrade, up to a maximum removal of around 4microns. The thickness variation of the plate can be easily corrected, and this can be very useful to produce constant thickness substrates. As the thickness variations are known as a limiting factor in the indirect slumping (hot and cold) techniques [10] and [11], this can represent "a must" towards high quality indirect slumping results. During the tests we have observed that the process can introduce stress into the substrates, therefore, further tests will be needed to assess this point and the definition of a process to release the stress will be required.

Based on these preliminary results, we have proven that the ion beam figuring of thin glasses is a feasible process. Further analysis will be carried out in the next months. Moreover, it is planned to extend the verification plan on silicon wafer, as this material is receiving growing consideration toward x-ray optics development [12].

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