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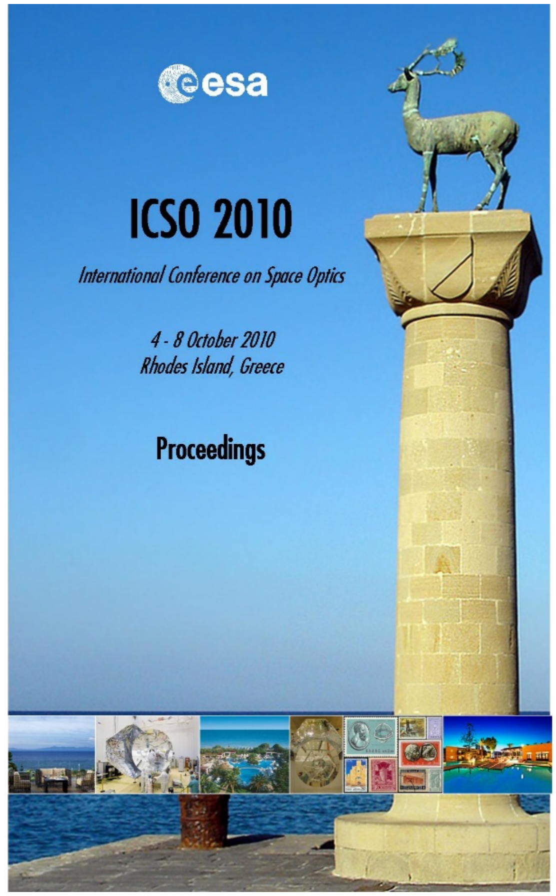


# *Hot Slumped Glass Segments with Reinforcing Ribs Technology for the Manufacturing of the IXO Telescope Modules*

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# HOT SLUMPED GLASS SEGMENTS WITH REINFORCING RIBS FOR THE MANUFACTURING OF THE IXO TELESCOPE MOUDULES

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ABSTRACT

The mirrors of the International X-ray Observatory (IXO) consist of a large number of high quality segments delivering a spatial resolution better than 5 arcsec. A study concerning the slumping of thin glass foils for the IXO mirrors is under development in Europe, funded by ESA and led by the Brera Observatory. We are investigating two approaches, the "Direct" and "Indirect" slumping technologies, being respectively based on the use of convex and concave moulds. In the first case during the thermal cycle the optical surface of the glass is in direct contact with the mould surface, while in the second case it is the rear side of the foil which touches the master. Both approaches present pros and cons and aim of this study is also to make an assessment of both processes. The thin plates are made of D263glass produced by Schott and are 0.4 mm thick, with a reflecting area of 200 mm x 200 mm; the mould are made of Fused Silica. The adopted integration process foresees the use of reinforcing ribs for bonding together the plates and forming in that way a rigid and stiff stack of segmented mirror shells; the stack is supported by a thick backplane. During the bonding process the plates are constrained to stay in close contact with the surface of the master (i.e. the same mould used for the hot slumping process) by the application of a vacuum pump suction. In this way the spring-back deformations and low frequency errors still present on the foil profile after slumping can be corrected. In this paper we present some preliminary results achieved during the first part of the project.

## I. INTRODUCTION

The International X-ray Observatory (IXO) is being studied as a joint mission by the NASA, ESA and JAXA space agencies [1]. The main characteristics are reported in Tab.1. The goal of the mission is the implementation of a X-ray focusing telescope with an unprecedented large effective area (3 m$^2$ at 1.25 keV, i.e. almost 7 larger than XMM) but still maintaining an optima good angular resolution (<5 arcsec HEW at 1.25 keV, versus 15 arcsec HEW of XMM). Under the support and coordination of the European Space Agency a study is being carried out in Europe to develop a technology for the fabrication and integration of the Wolter I mirrors of IXO based on thin glass slumped segments. The present study is led by the Brera Astronomical Observatory - INAF (OAB) and involves other institutes like MPE and small enterprises like BCV-Progetti (Milano, Italy), ADS-International (Lecco, Italy) and Media Lario International (Bosisio Parini, Lc, Italy). Both OAB and MPE were involved in preliminary activities devoted to study of mirror production based on the slumped glass foils based on internal resources [2]. This approach should be considered as a backup technology for the "Pore Optics" technology investigated so far by ESA in collaboration with the Cosine company [3]. It should be noted that the slumped glass technology is also being studied, since a few years, by the US groups involved in the IXO optics development [4]. However our study contains a number of innovative technology elements and solutions different from those followed in USA, concerning both the foil forming processes and the integration method.

This study has been divided in two phases. The Phase 1, started in Sept 2009, at the moment of the preparation of the present paper, has been just completed . The activities have been mainly dedicated to the assessment of the slumping technology, in order to find the best approach for the segment manufacturing, and to a preliminary investigation of the integration and assembly concept, including a possible design of the IXO optics module based on thin glass plates [5],[6]. In the following sections we will present the main achieved results. The Phase 2 of the project will start in September 2010 and will last after 18 months.

**Tab. 1.** Main IXO optics parameters

| | |
|---|---|
| **Configuration** | Wolter I |
| **Min – MAX Radius of clear aperture** | 0.25 – 1.9 m |
| **Total mirror assembly mass** | 2 tons |
| **Effective area @ 1.25 keV and @ 6.50 keV** | 3 m$^2$ / 0.65 m$^2$ |
| **Field of view @ 1.25 keV** | 18 arcmin (diameter) |
| **HEW across the FOV @ 1.25 keV** | 5 arcsec |

At the end of Phase 2 a prototype of X-ray Wolter I unit, formed by 20 “tandems” of parabolic plus hyperbolic segments assembled together will be developed; of the 20 couples of segments at least 3 of them will be fully representative while the remaining ones have to be considered dummies.

## II. DEVELOPMENT OF THE SLUMPING TECHNOLOGIES

Two approaches, the “direct” and “indirect” hot slumping techniques (Fig.1), have been considered for giving the shape to the thin foils (Fig. 1):

- Direct Slumping: the optical surface of the Mirror Plate (MP) is the side of the glass plate that comes in contact with the mould during the slumping. This technique foresees the use of convex moulds. Normally the glass foil slumps onto the mould by means of its own weight. A variant of this technique that has been developed and tested by INAF-OAB foresees the use of an actively applied pressure on the glass to force it in contact with the mould.

- Indirect Slumping: in this case the back surface of the MP is in contact with the mould. This technique uses concave moulds. In this case the glass slump into the mould using its own weight (that is by gravity). This technique has been developed and tested during this study by MPE, a subcontractor of INAF-OAB in the frame of this activity.

During the Phase 1 of the study for both direct and indirect slumping techniques moulds with cylindrical configuration, instead of parabolic and hyperbolic configurations that would have been needed for making real Wolter I mirrors, have been used. A reduced cost and a shorter fabrication time drove that choice, that in any case enabled to compare the performance of the direct and indirect slumping approaches in the capability to replicate the shape of the master and to produce segmented X-ray mirrors. In total four moulds (two concave and two convex) were designed by OAB and produced by Hellma Optik (Jena, Germany). The masters are made in Fused Silica, with a square base of 250 mm x 250 mm, a thickness of 50 mm and a radius of curvature of 1 m. The moulds have been coated via e-gun evaporation with a first layer of Cr of 5 nm thick and a second layer of Pt 50 nm thick. While the Pt film, due to it high melting point (1772.0 °C) and its very low chemical reactivity acts as a release and anti sticking agent between the glass foil and the Fused Silica mould, the layer of Cr has been added to enhance the adherence of Pt to the mould surface. The foils selected for thermal slumping were segments 0.4 mm thick made of the Schott D263 borosilicate glass.They have been cut by laser cutting at MDI Schott to the final slumping dimension of 200 mm x 200 mm.

One of the main advantages of the “direct slumping” approach is that is not sensitive to the thickness variations of the glass foil, since the mid frequency irregularities caused by this problem are transferred to the back side of the mirror plate. Moreover, the capability developed at INAF-OAB to apply a pressure on the glass foil during the slumping process forces the foil to stay in close contact with the mould and then to replicate its profile with a good accuracy, apart from some spring back effects after the release. The whole process takes place in a stainless steel muffle (Fig. 2 A-B) where Argon (Ar) is fluxed in order to protect the glass foil and the mould against the contamination of dust produced in the oven and the presence of oxygen and humidity in the air. The muffle also guarantees a more uniform temperature in the environment surrounding the mould. Once the muffle is closed and positioned in the oven, the thermal cycle is started. The maximum temperature of the process is between 570 and 600 $^{o}$C depending on the performed test. After a couple of hours that the max temperature of the process is reached (and maintained), an uniform pressure is applied ranging from 50 to 150 g/cm$^2$. The cooling down rate is normally performed very slowly (2.5 – 10 $^{o}$C/hour) in order to reduce as much as possible the temperature gradient in the mould and in the glass, that might introduce some deformations and spring back on the mirror plate after the separation.

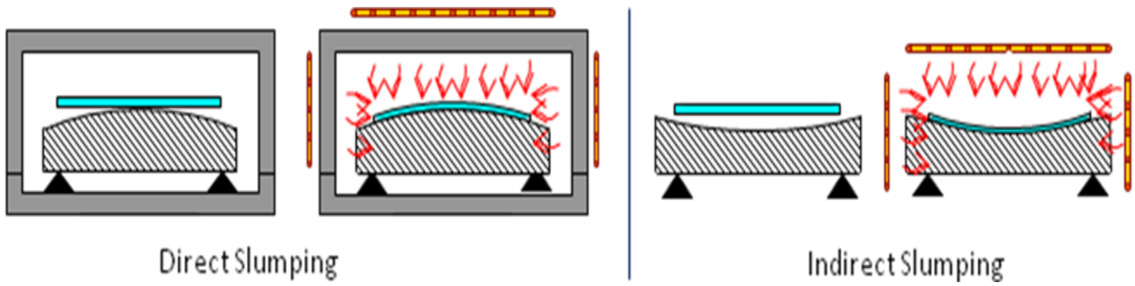



**Fig.1.** Schemes of the slumping techniques investigated in the present study: “direct” (left side) and “indirect” (right side) slumping techniques.


**Fig. 2.** (A) Muffle used for the direct slumping; (B) fused silica mould in the muffle; (C) mould and foil into the furnace used for the indirect slumping tests.

The indirect slumping technique is currently investigated at MPE and foresees the slumping of the glass sheets onto a concave mould. The reflecting surface of the foil is not in contact with the mould surface and in that way the very good microroughness of D263 plates (a few Angstrom rms) is completely preserved. Also, no pressure applied to get the glass in full touch with the mould but just gravity. However, due to possible inclusion of air in the middle of the mould, if the edges slump down first, a central hole is needed to enable the air to escape. This can be supported by a vacuum pump connected with the central hole of the mould, to exert suction and ensure a proper contact of the glass to the mould surface. A main drawback of this method concern the thickness variations of the glass foil that for P/V values larger than +/- 0.5 μm may strongly affect the final figure of the slumped optical surface with the introduction of mid frequency errors. At present the thickness uniformity of the glass foils D263 is of the order of +/- 3 μm and +/- 5 μm for the T and ECO kinds respectively. In both cases the foils would need to be grounded and polished to ensure an uniform thickness. Moreover the absence of the mould and of the Ar environment increases the risk of contaminations during the slumping process.

## III. THE INTEGRATION CONCEPT

The thermally slumped foils, after the removal from the forming mould, can be affected by some spring-back effect (due e.g. to the different in the CTE values of the mould and foil materials or to the generation of some thermal gradient between the center and the edges of the plate during the slumping process). Moreover the handling of the thin foils for the integration is very difficult and the risks to introduce deformations in their shape during the integration is very high. In order to resolve these problems, the integration concept we have envisaged is based on the fundamental assumption that for a thermally formed plate produced via direct slumping the shape achieved after slumping can be restored if it is placed again onto the forming mould and a vacuum suction is applied to constrain the surfaces to stay in close contact (Fig. 3). In that way the ideal shape after slumping is restored, making much easier the handling of the plate for the integration process. In a similar way, for the case of plates produced via indirect slumping, one can make use of a convex integration mould with proper shape for obtaining the same result. At this regard, the gluing of reinforcing ribs can be applied to the rear of the plate when it is kept adherent to the mould by vacuum suction. With this method it is possible to connect together two consecutive glass plates and, iterating this procedure, X-ray Units made of stacks of plates can be created. It should be noted that the ribs will guarantee a high rigidity and stiffness to these stack structures of integrated plates, keeping them at the correct positions and shapes. A breadboard of three flat stacked plates was developed during the Phase 1 (Fig. 4).

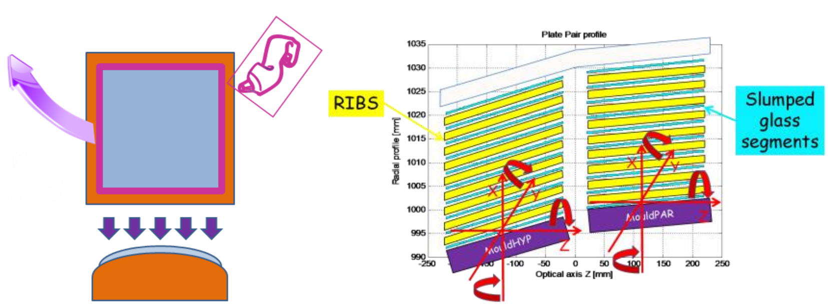



**Fig. 3.** Left side: with the use of the vacuum suction on the formed foil placed on the mould the shape after slumping is restored, correcting the errors due to the spring back after the detaching; in that way the foil can be easily handled during the integration. Right side: iterating the procedure it is possible to create an X-Ray Unit made of several pairs stacked together; for this purpose reinforcing ribs are used to connect each plate to the next one.

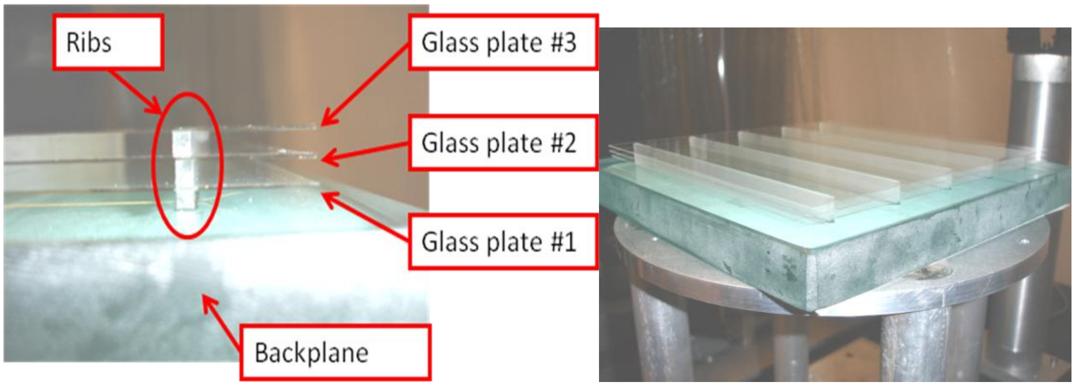



**Fig. 4.** Breadboard of three flat stacked plates developed during the Phase 1 of the project. The first foil is connected to a thick glass backplane.

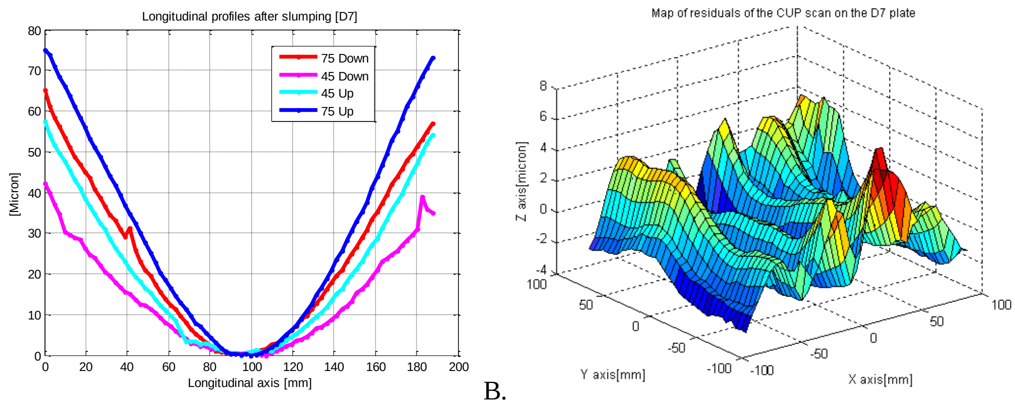
During the integration, the optical surface of the glass is kept in contact with the mould and then the mould of each mirror plates may be taken as a geometrical reference for the alignment of the plates in the stack. Using the mould measurement, each plate pairs (parabola + hyperbole) will be firstly aligned to each-other and then integrated into the stack by gluing it to the previous plate pair.

It is important to point out that the machining of the ribs to precisely follow the curved rear of the figured glass plate surface is not needed; on the contrary the ribs have just to be tapered to a coarse conical profile, with differences > 1 μm with respect to the curved surface. All the differences between the shape of the rib and foil at macro and microscopic level will be compensated by the glue filling the gap. At this regard, the glue thickness layer is set to be 50 μm, which is not only able to compensate the differences from the desired and real profiles of the ribs but, also corresponds to the optimal values for the toughness and adherence of the glue (this aspect has been proven after careful experimental tests). In order not to introduce deformations in the integrated plates, the glue should be characterized by a very low shrinkage. Moreover, the glue strength should be compatible with the mechanical/optical design, have a CTE compatible as much as possible with glass and presenting a low outgassing. The selected glue for phase A is epoxy Masterbond EP30-02.

## IV. DEVELOPEMENT AND INTEGRATION OF CYLINDRICAL SLUMPED FOILS SAMPLES

A number of cylindrical shaped glass foils 200 mm x 200 mm have been developed during the Phase 1 of the project using both the direct and indirect slumping technologies, aiming at obtaining the best set-up parameters. In the direct slumping case, the initial profiles were very different from the shape of the mould, presenting sags more than 200 μm larger than the mould profile. By changing the pressure and temperature parameters and optimizing the technique, the profiles have been improved, reducing the P-V error of 3-4 times of the foils before the integration. By the way these errors have to be considered at low spatial frequency (regarding in particular the first harmonics of the power spectrum). Therefore the integration of a glass foil onto a backplane by means of the reinforcing ribs, following the above described procedure, allows us to largely reduce them. In fact, before the integration the foil is forced by vacuum against the same mould used for the thermal shaping process, so the spring-back errors can be corrected. After that the plate has been fixed to a thick backplane by means of the ribs application, then the vacuum is released. The glued connections to the ribs partially freeze the plate shape but still some spring back, due to stored elastic energy, is expected depending on the distance between two adjacent ribs. The present design foreseen using 5 ribs for plates 200 mm wide, so that the distance between them is 40 mm. As an example of this capability of the adopted integration method, on the left of Fig. 5 is shown the result of the integration of sample D7 slumped with direct technology. The initial PV error was of about 80 microns but after the integration the same profile was reduced to just 4-5 microns, as visible in the 3-D maps measured with a new optical profilometer developed in the context of the contractual activities [7]. The angular resolution resulting from the metrology resulting after the integration is of 20 arcsec HEW. This result is in line with the FEM simulations that has been preformed. It should be noted that, when the initial shape of the glass is characterized by mid frequency errors (of the order of 40 mm space wavelength or smaller) the correction capability is much lower.

The HEW due to the scattering for each sample has been evaluated from the measured micro-roughness data (Wyko+AFM+XRS) in the 0.1-660 μm spatial wavelength range (for indirect slumping the data coming from contaminated regions have not been considered).




A. B.

**Fig. 5.** (A) Longitudinal profiles of a slumped glass, produced via direct slumping foils, taken at +/- 45mm and +/-75mm from the centre before the integration. (B) Map of the same sample after integration with ribs on a backplane. The corresponding angular resolution is 20 arcsec HEW.

## V. MECHANICAL AND OPTICAL DESIGN OF THE IXO OPTICS AND INTEGRATION OF THE X-RAY OPTICS UNITS

The realization of the entire IXO mirror assembly based on glass slumped foils relies on the principle of hierarchical integration of subsystems (Fig. 6). After the shaping of a number of foils with parabolic and hyperbolic shape they are stacked and connected together through glued ribs, whose aim is to maintain the mirror foils in their mutual correct position. The proposed “X-ray Optic Unit” (hereafter XOU) integration procedure requires parallel integration of both parabolic and hyperbolic stacks onto a common monolithic supporting structure, which will become part of the XOU structure. The integration of the plate pairs is performed with high precision alignment in order to get the desired HEW performances. The XOU, once qualified and calibrated, are integrated on ground onto petals that, on turn, will be assembled together to form the entire optics system of IXO. In line with this integration process, the terminology hereafter reported has been defined:

- **Mirror Plate (MP)**: Glass foil forming an azimuthal fraction of the parabolic or hyperbolic surface for a given shell with Wolter I configuration.
- **Plate Pair (PP)**: Pair of Mirror Plates, one parabolic and one hyperbolic.
- **X-Ray Optical Unit (XOU)**: Elementary optical unit composed of stack of glass Plate Pairs connected each other by glued ribs. An outer structure allows the handling, calibration and connection to the Mirror Petal Structure.
- **Mirror Petal Structure (PS)**: Intermediate Level Structure containing a number of XOUs. Several PSs are needed to azimuthally cover the entire aperture of the IXO Telescope.
- **IXO Mirror Assembly (FMA)**: The whole optics assembly of the satellite, comprising optical and structural parts i.e. Mirror Optical Bench (MOB) equipped with PSs (if any) populated with the XOUs made by stacks of MPs.

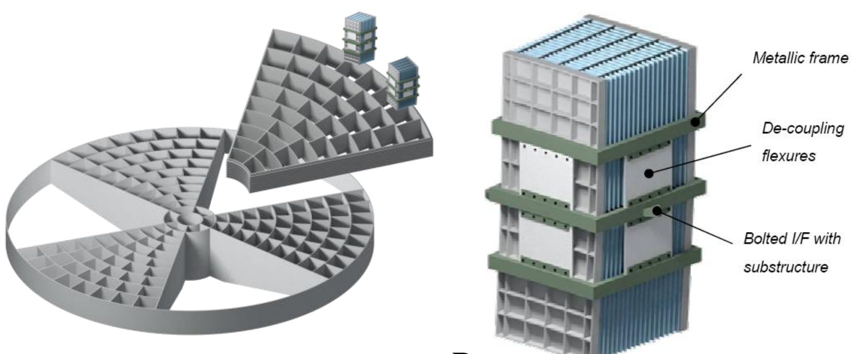



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**Fig. 6.** (A) IXO Hierarchical concept assembly and (B) X-Ray Optical Unit

In the present design it has been assumed that the radii of the Wolter I shells range between 250 mm and 1900 mm, for a total of 375 confocal mirror shells . The mirror units are based on a “double plate stack” configuration (with two structural thick plates placed on the front and the rear of the stack). The stack width is ≈ 170 mm and, on average, it can host 40 plate pairs (2 plates 200 mm x 200 mm x 0.4 mm each). Five glass tapered ribs (with the thickness variable from 3 to 5 mm, depending on the shell radius) are needed to fix each plate pair. For the present configuration the Mirror Assembly consist of 246 XOUs (41 XOUs for each of the 6 petal) arranged in 9 nested rings. The layout of the modules has been assessed considering a radial spacing between the optical units of about 40 mm, and an azimuthal spacing of about 35 mm. These values (to be intended at hyperbola-parabola interface plane) represent the minimum spacing considered allowable for I/F accommodation; in addition they are assumed to provide an adequate accessibility for regulations during integration phases.

In order to carry out the integration of plates pair into the XOU a dedicated Integration Machine (hereafter IMA) has been designed, in accordance with the integration process (Fig. 7). The IMA will align two separate moulds carrying each one its glass plate and then place at the same time the couple in position for their integration into the XOU. In order to align the plates in the stack, the parabola and hyperbola moulds are assumed as reference for the front reflecting surface of each plate. The position and the orientation of the moulds will be carefully measured with a 3D metrology machine; these data will be used to align together the two parabolic and hyperbolic moulds and get the right common orientation between the two plate of a pairs. The 3D machine (1μm accuracy RMS needed) measures the frame of the mould external to the glass plate. The output are the radii of curvature at the top and at the bottom of the moulds and the longitudinal profiles sampled with 1 mm steps. These data will be used to find the best locations for the plate horizontal positioning and tilting, evaluated after having performed a ray-tracing simulation. The most demanding requirement that drives the design of the IMA is the relative attitude between the two moulds to be better than 0.25 arcsec around the around the Y axis. Such an angle must be kept constant across the overall curing time for gluing the ribs to the plates, which amounts to several hours. An attitude error of 0.2 μm on a 200 mm baseline corresponds to ~ 0.2 arcsec error: the two moulds have to be kept aligned better than this level. Even assuming a rigid temperature control of the integration environment, the differential thermal deformations of the mould and mirror module support structures could introduce attitude errors well above the allowed ones. In order to reach such a demanding specification, the active control of the relative attitude of the two moulds during the integration time has been considered the most appropriate approach. The integration machine has been completely designed and simulated during the phase 1 of the project. It will be realized during the Phase 2 and the breadboard so realized will be used for the integration of the 20 pairs prototype to be developed and calibrated with X-rays by the end of the activities.

REFERENCES


[1] J. A. Bookbinder, **"**An overview of the IXO Observatory"**,** *Proc. SPIE*, Vol. 7732, 77321B (2010)

[2] M. Ghigo, et al. "Hot slumping glass technology and integration process to manufacture a grazing incidence scaled prototype for the IXO telescope modules", Proc. SPIE Vol. 7437-22 (2009)

[3] W. W. Zhang et al., "Mirror technology development for the International X-ray Observatory mission (IXO)", *Proc. SPIE*, Vol. 7732, 77321G (2010)

[4] M. J. Collon, et al., "Silicon pore x-ray optics for IXO", *Proc. SPIE*, Vol. 7732, 77321F (2010)

[5] M. Ghigo et al., "Hot slumping glass technology for the grazing incidence optics of future missions, with particular reference to IXO", *Proc. SPIE*, Vol. 7732-11, (2010)

[6] M. Civitani et al., "IXO X-Ray mirrors based on glass slumped segments with reinforcing ribs: optical and mechanical design, image error budget and optical unit integration process", *Proc. SPIE*, Vol. 7732-146, (2010)

[7] M. Civitani, M. Ghigo, O. Citterio, L. Proserpio, D. Spiga, G. Pareschi, "3-D characterization of thin glass segmented X-ray mirrors via optical profilometry", *Proc. SPIE*, Vol. 7803-19, (2010) in press


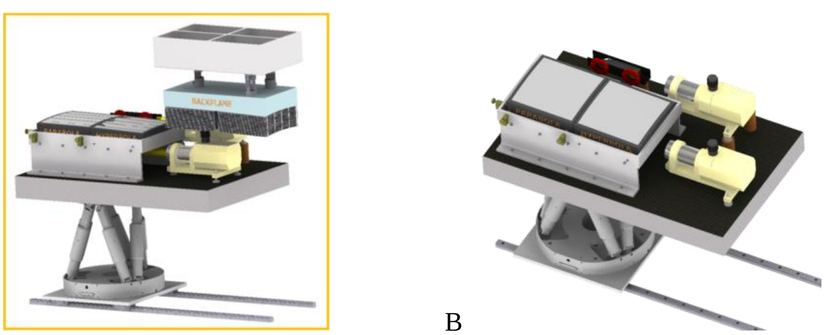

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**Fig. 7.** Schematics of Integration Machine (IMA) under development.