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JIM: a Joint Integrated Module of glass X-ray optics for astronomical telescopes

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ABSTRACT

For several years, the Max-Planck-Institute for extraterrestrial Physics in Germany (MPE) and the Astronomical Observatory of Brera in Italy (INAF-OAB) have been studying the slumping technology for the manufacturing of segmented glass X-ray optics for astronomy. Despite some differences in their specific approaches, the synergy of the two institutes has always been good, focusing on the common goal of developing a technology able to meet the outstanding requirements for future X-ray telescopes: i.e. large collecting areas, low mass and good angular resolution. This synergy has in the last year resulted in an active collaboration for the production of a Joint Integrated Module (JIM) that puts together the expertise of the two research groups. In particular, the indirect slumping approach of MPE has been employed for the manufacturing of X-ray mirror segments that have been integrated into a kind of X-ray Optical Unit following the approach developed at INAF-OAB. The module has then been tested in X-ray at the MPE PANTER facility, in Neuried. The several steps and the results of this joint activity are reviewed and discussed in this paper.

Keywords: Joint Integrated Module (JIM), X-ray Optical Unit (XOU), Slumped Glass Optic (SGO), X-ray Mirror Segments, Integration Machine (IMA), Slumping Technology, Indirect Slumping, X-ray telescope

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1 INTRODUCTION

“Hot Slumping” is a technique in which items are made in an oven by shaping glass foils over moulds at high temperature: The viscosity of glass changes in such a way to allow its bending and slumping onto the mould, coming in contact with its surface and replicating its shape. The original glass micro-roughness can be preserved with the correct tuning of process parameters. Being a fast replication technique with an intrinsic low manufacturing risk and high level of activity parallelization, it is well suited for the mass production of modular elements. This makes the slumping technology a perfect candidate for the manufacturing of future astronomical X-ray telescopes that need in general to be lightweight and stable in the space environment (meaning that glass represents a good choice of material), still guaranteeing a high collecting area (meaning lots of thin mirror segments arranged in a large number of basic optical modules that provide a large filling factor of the accessible geometric area) and good angular resolution (meaning high degree of shape and roughness control during production process). Its application for X-ray telescope production has indeed already been demonstrated with good results through balloon (HEFT) [1] and space experiment (NuSTAR observatory) [2]. However, the current status is not yet suitable for the more demanding mission planned for the future and developments are on going to enhance the optics resolution and fully exploit the potentiality of the technique. At this regard, several groups in the world are involved in research and development activities connected to the several aspects and approaches of the slumping technology [3-8].

In particular, **the group at MPE is developing an indirect hot slumping technique founded on two basic ideas:**

- **To produce by thermal forming precise monolithic segments of Wolter I mirrors:** The parabolic and hyperbolic part of the Wolter I design are slumped together in a single piece and this guarantees certain stiffness for the segments and easier alignment during integration. On the other hand, it requires more efforts in the slumping mould production because of the kink area: the possibility of monolithic mould manufacturing has been demonstrated with only a few mm area losses around the kink. The approach at MPE is an indirect one,

meaning that the mirror segments being shaped comes in contact with the mould only on the back side and this allows to preserve the glass microroughness on the optical side, essential for X-ray reflection.

- **To integrate each single segment through glued-points at its perimeter without introducing stresses and deformations:** This is the stress-free integration paradigm that takes advantage of the monolithic shape of the segments during the alignment step. On the other hand it can work only with precise slumped plates placing strict requirements in terms of acceptable slumping results.

Conversely, **the group at INAF-OAB is following a different philosophy:**

- **To cylindrically shape the glass segments with a direct approach,** in which the optical surface of the mirror being formed comes in contact with the mould: In this way the manufacturing of the moulds in terms of shape is less demanding even if the requirements in term of roughness are higher due to the risk of degrading the glass surface finishing because of the contact with the mould during the slumping process.
- **To precisely shape the glass to the Wolter I design during assembly:** This is done **with a step of cold slumping**, making use of precise integration moulds on which the glasses are forced by vacuum suction. The segments are stacked one over the other with glued structural elements (named ribs), starting from a backplane rigid structure, and the shape of integration mould is frozen into the glasses, except for some spring back effects. This approach offers the great advantage of the possibility of correcting long spatial wavelength deformations left in the mirror segments by the hot slumping step: Conversely, stresses are introduced in the plates and their impact on the structural/mechanical behavior of the entire telescope needs to be deeply analyzed.

It is clear how the two approaches are different not only for technical realization aspects but because of the philosophies behind. There is not yet sufficient knowledge to decide for one specific approach since each one carries its own pro and cons. It is worth to further analyze and develop both to try getting the best from each one. This is exactly what we start doing this year: taking advantage of the good synergy between the group at MPE and the one at INAF-OAB, we try to put together our expertise and mutual experience in a mixed approach for the realization of a glass X-ray Optical Module. This results in JIM (Joint Integrated Module) in which glasses have been slumped following the indirect approach pioneered by MPE and integrated following the cold slumping phase established by INAF-OAB, which developed a dedicated machine for the scope, named Integration Machine – IMA [9]. The collaboration was advantageous for both groups: while MPE had the possibility to check the behavior of its own glasses with a different integration configuration and get experience on integration mould manufacturing, INAF-OAB had the opportunity to check its process with concave moulds instead of the convex ones used so far. In this way the optical side of the segment is totally available for metrology during its integration consenting its checking, among the other available metrological systems, with the deflectometry system set up by MPE [10].

This paper describes the several steps of the activities that led to manufacture and test JIM and reports on the results: In particular, in section 2 the characteristics and components of JIM are described; in section 3 the integration procedure is summarized; section 4 reports on JIM expected performances as evaluated by optical metrology; section 5 and 6 shows the results of PANTER X-ray tests and vibration tests respectively; while lessons learned are listed in section 7.

2 JIM CHARACTERISTICS AND COMPONENTS

JIM is a prototype module of Segmented Glass X-ray Optical Unit, composed by 5 layers of slumped segments stacked on a backplane through the application of glued structural elements named ribs. The layers are composed of monolithic segments of Wolter I design, i.e. with the parabolic and hyperbolic part formed together in a single piece of glass. All the layers are nominally identical so they are not meant to have a common focus: Instead, they are integrated parallel one to each other so that their foci lie on a line, separated by the same distance of two consecutive layers. This distance is given by the height of the ribs, which run along the glasses in longitudinal direction (i.e. parallel to the optical axis) and keep the segments in their mutual position and alignment. The stack of layers is started with a backplane that gives rigidity to the entire module. Figure 1 and table 1 show the main characteristics of JIM: The layers are 200 mm long x 100 mm wide, with a thickness of 0.4 mm. They are segments of Wolter I mirror with focal length of 7500 mm and Radius of Curvature at the intersection plane of 374.157 mm. Each glass segment is connected to the consecutive ones through the use of 8 glued ribs: 4 on the parabolic and 4 on the hyperbolic side of the segments. The ribs are around 28 mm distant one to each other and they measure 92 mm x 2 mm, with a height of 2.8 mm that gives the space between layers. They

are glued in a radial configuration for conformity with the flight-like radial module, considering the minimum distance from the edges of 5 mm, necessary for the integration procedure. The backplane is larger so that it can be positioned on the Integration Machine (IMA) without additional interfaces with respect to the standard one. The whole structure is not completely representative of a flight module since the main scope of JIM was to further enhance the knowledge of the MPE-OAB combined methodology in the cheapest, faster and most effective way permitted by the available tools.

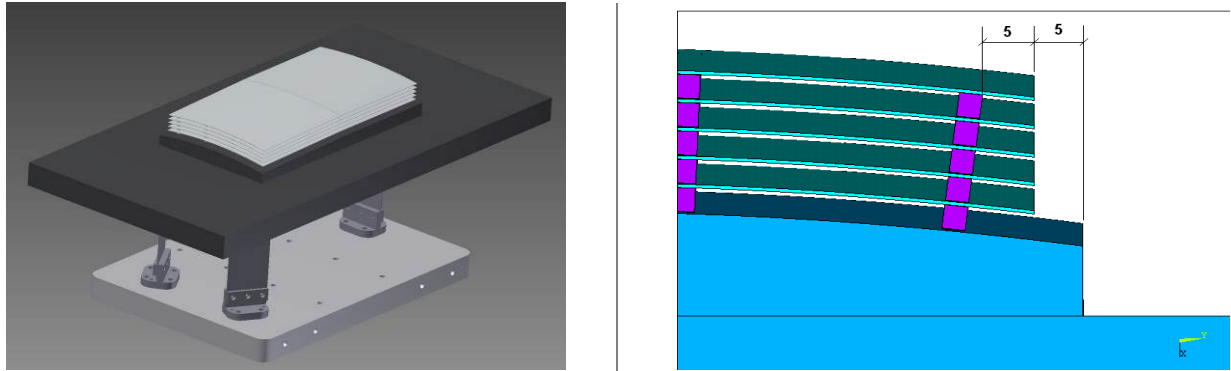


Fig. 1: (Left) Drawing of JIM prototype: JIM consists of 5 glass segments combining parabola and hyperbola parts of the Wolter I design in one piece. The glasses are stacked gluing in between them 8 ribs per layer. The first set of ribs connects the stack to a backplane which is attached to the standard IMA interface through flexures. (Right) Details of glass layers and ribs positioning at the edge: Although the layers are of identical geometry, the radial ribs structure was chosen for conformity with flight-like radial module.

Table 1. Components of JIM and their characteristics

Component	Characteristics
Segments	Schott glass D263 5 layers of Wolter I monolithic segments (PAR+HYP together) $f = 7500$ mm $RoC_{kink} = 374.157$ mm Dimension = 200 mm x 100 mm (long. x wide) Thickness = 0.4 mm
Ribs	Glass BK7 8 ribs per layer: 4 on PAR, 4 on HYP side (total of 40 ribs) Plane parallel ribs Planarity Peak-to-Valley = 5 μ m Dimension = 92 ± 1 mm x 2 ± 0.1 mm (long x wide) Height = 2.804 ± 5 μ m
Backplane shape	Lightweight Titanium Ti-6Al-4V Convex Wolter I shape (equal to the segments) $CTE^+ = 8.6$ ppm/K (good matching with the glasses = 7.2 ppm/K) Dimension = 430×210 mm ² (interesting area 210×110 mm ²) Height = 35 mm (maximum height) Weight* = 9.5 kg Interfaces to IMA holder with steel pads with flexures
Glue	MasterBond EP30-2 Meets low outgassing specification for space applications Very low shrinkage Curing time ~ 24h @ RT [#] (or more rapidly at elevated temperatures) Working time = 20-25 minutes

*CTE = Coefficient of Thermal Expansion, *The weight is NOT representative of the flight module: heavier to produce it faster and cheaper, [#]RT=room temperature

The following subsections report details about the production or procurement of all the elements that form JIM.

2.1 Optical element production: Mirror segments slumping

The 5 mirror segments have been realized at MPE through indirect slumping [11], [12]. The glasses have been thermally formed already at their required dimension of 200 mm x 100 mm, i.e. there was no cutting step after slumping. The used glass type is D263 by Schott whose Coefficient of Thermal Expansion (CTE) matches quite well the one of the HP1465 Porous Ceramic mould. The mould was the one that could be reproduced best at the time of being so it was used even knowing that its surface shape contains critical waviness, as shown in figure 2, which are replicated during the forming process. The HP1465 Porous Ceramic offers the great advantage of no need of separation layers and allows for pumping utilization during the forming process to improve the shape replication. However, the open porosity plays also an important role during shape metrology, making the data acquisition difficult and noisy. This leads to a limitation in the polish-ability of the material, which results in a mould of around 65-70" HEW (Half Energy Width). New metrology and polishing techniques are currently under evaluation for the porous ceramic material, and new moulds in other materials with better polish-ability are under consideration [13]; meanwhile we can continue deepening the knowledge of the process with the available porous ceramic mould.

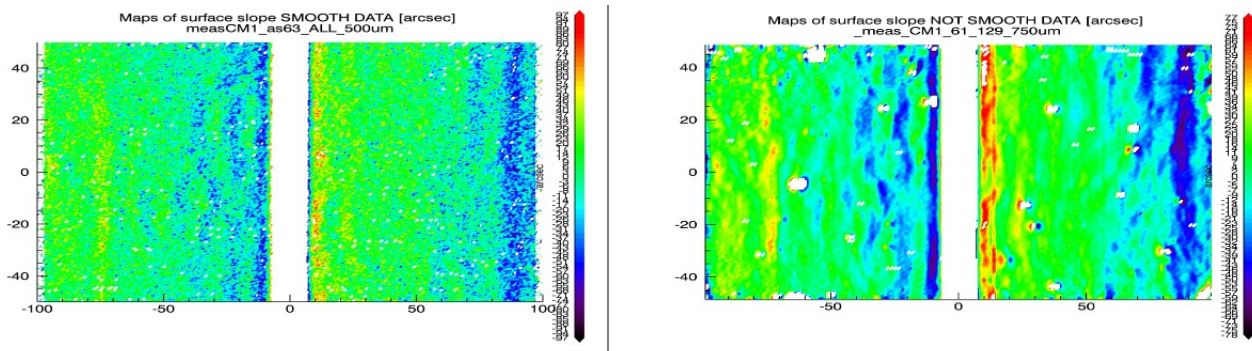


Fig. 2: (Left) waviness presents in the currently available HP1465 Porous Ceramic shown in terms of slopes, which is replicated in the glass during slumping (Right).

The five glasses have been slumped with a cycle lasting for almost 3 days, because of the very low heating up and cooling down rates not exceeding $10^{\circ}/\text{h}$ during the important phase of the cycle (i.e. above the annealing temperature of the glass) and maximum temperatures ranging from 605°C to 620°C . After the shaping, they have been measured with a CHRcodile sensor on Ipkf table and then cleaned for the integration. They have been assembled in a very simple structure for a first X-ray test in PANTER and then removed to be shipped to INAF-OAB for the final integration in JIM. Their metrology is reported afterwards in section 4.

2.2 Structural elements procurement: Backplane, ribs and glue

2.2.1 Backplane

A backplane element is needed to start and offer rigidity to the mirror segments stack. It also provides the connection points for JIM positioning on the IMA and during tests at PANTER: Pads and flexures are screwed for the purpose on its back side. The backplane is realized in a material with CTE similar to that of the glasses, to avoid stresses and deformations due to temperature differences in the various laboratories and during transport. After a thorough analysis of the material properties and consideration of costs and delivery time, the material titanium Ti-6Al-4V was selected. The backplane has been produced by the company Lex GmbH Präzisionsmechanik; the flexures and the holding plate were realized in steel by the MPE workshop on drawing of OAB engineers. The base dimensions are larger than strictly required for the glass layers in order to avoid additional interfaces for the IMA. The part is 210 mm large and 430 mm long, with a maximum thickness of 35 mm. Its backside has been lightweight to be compliant with the load capability of the IMA. The area of interest for the integration of the slumped segments is the 210 mm x 110 mm area in the centre, which has been mechanically machined at the nominal Wolter I shape of reference for the glasses: this shape is convex due to the chosen approach of the so called indirect integration, meaning that the segments touch the integration mould from their backside (the nomenclature "indirect" is coming from the analogy with the thermal process). This central area of interest is 15 mm elevated with respect to the surrounded area to guarantee the necessary accessibility during

integration activities. The backplane was manufactured with standard mechanical procedures that guarantee a fast and cheap delivery: the shape accuracy is slightly better than $\pm 10\text{ }\mu\text{m}$. This is acceptable because the thickness of glue that was considered is $50\text{ }\mu\text{m}$, thus it can absorb these residuals.

2.2.2 Ribs

The ribs are essential structural elements that keep the glass layers in their mutual alignment and position, while providing mechanical rigidity to survive the loads of the critical phases of the missions (typically the launch). In the case of JIM, plane parallel ribs are the best choice since the equal layers were meant to be mounted parallel one to each other. For financial and time reasons, the ribs have been provided by INAF-OAB from a batch of already available BK7 parallel ribs purchased for the integration of a previous prototype (XOU_BB, [14]). Since they were longer than necessary, they have been manually cut into parts of 92 mm each. The decision of using 4 ribs per layer comes from Finite Elements Analyses simulations on their correction effects on slumped segments. The free area between ribs is around $\sim 30\text{ mm}$, close to the $\sim 35\text{ mm}$ considered by OAB for previous prototypes [15]. Considering the major rigidity around the intersection plane, given by the bending of glass, we decided to leave 4 mm per side between the two halves of the ribs to avoid the residuals of up to $20\text{ }\mu\text{m}$ typical for a 4 mm wide band around the kink zone.

2.2.3 Glue

The glue used for the JIM assembly is EP30-2 by Master Bond. It is a low viscosity, two part epoxy system for high performance bonding, formulated to cure also at room temperature. It has been selected for the reason that the two components are 100% reactive and do not contain any solvents or volatiles: Therefore, the dimensional stability and shrinkage upon cure are remarkably low. Furthermore, it meets the low outgassing requirements set for space applications. The working life of 25 minutes is compatible with the IMA operation of alignment and integration. The curing time is of about 24 h at room temperature, and can be shortened at elevated temperatures. EP30-2 bonds well to a variety of substrates including glass and metals, and this permits to consider metallic backplane without needs of special preparation of its surface. The glue was already available at INAF-OAB since it was used also for the previous prototypes they integrated in the past years [15].

3 JIM INTEGRATION

The JIM prototype module was assembled following the cold slumping approach proposed by INAF-OAB, using the ad-hoc designed Integration Machine available in the INAF-OAB laboratories in Merate [9]. The basic idea is to impart the correct Wolter I shape to the segment being integrated by vacuum suction on a precisely machined integration mould, and then glue it through ribs on the supporting structure (backplane) or on the previous layer in the module. When the glue is cured, the vacuum suction and integration mould can be removed: The correct shape is frozen in the segment except for low spring back effects. More in details, the integration itself consists of several steps: First a set of ribs needs to be attached to the backplane as a space holder for the first layer. For this purpose, the ribs are placed on the integration mould kept in position by a rib mask, glue is dispatched on them, and the IMA stage is raised up to the backplane position so that the ribs glue on it. The next step is the gluing of the first glass. The glass is put on the integration mould using an alignment mask for its positioning and vacuum suction is applied, through the use of electrostatic film mask around glass edges, so that the glass adopts the shape of the mould. Now a layer of glue is dispatched using the rib masks, and then the IMA stage is moved into the right position below the backplane in order to glue the glass on the first set of ribs with a glue layer of the wanted thickness. These steps are repeated for all the other layers.

The rib-based integration method realized with the IMA opens the need for several masks and interface parts. These parts have been designed by OAB and produced mostly in the MPE internal workshop, mainly in Aluminium, with some minor parts made of steel. They include: 1) The holder for the integration mould on the IMA, which was originally designed to accommodate larger size integration moulds; 2) the backplane holder on IMA, with pads and flexures; 3) the mask to align glass segments on the integration mould; 4) the masks to align the ribs: Five rib masks were needed to align the ribs properly on the glasses during integration, to account for the radial design.

3.1 Integration mould

The integration mould is a fundamental element for the assembly approach of INAF-OAB since it is the tool used to precisely shape the mirror segments. In the past, integration moulds have been realized in glass materials by means of

optical precision polishing techniques. For JIM, due to time and cost constraints, we decided to explore the possibility of machining a metallic integration mould through diamond turning. The selected material was Al alloy 5083 because the manufacturer LT-Ultra has a lot of knowledge on the machining of this material, which has normally a fast and cheap delivery. The major concern was the effect of temperature variation during integration because of the higher CTE of Al with respect to the glass: However, the IMA machine is inside a room control in temperature at better than $\pm 0.1^\circ\text{C}$ level and FEA simulations suggests a negligible effect on JIM. Since the considered approach is the indirect integration, the mould has a convex shape, with the same Wolter I profile as the glasses. Its basic dimensions are 160 mm x 260 mm, with a maximum height of 55mm. The realization was very fast (three full working days on the machine) and indeed shows the great potentiality of this approach for the production of integration moulds, which could be beneficial in view of mass production. As shown in figure 3, the mould accuracy in shape is better than $\pm 2.5 \mu\text{m}$ PtV (peak to valley) on the total surface and it accounts for the HEW in single reflection of around $10''$ in the central $200 \times 100 \text{ mm}^2$ area of interest for the segments integration. There is still some waviness left by machining (see figure 4), probably due to vibrations: This was not critical for JIM but might be for improved glasses when we aim at reaching better than $5''$ HEW for the complete module; therefore we are currently working on removing it.

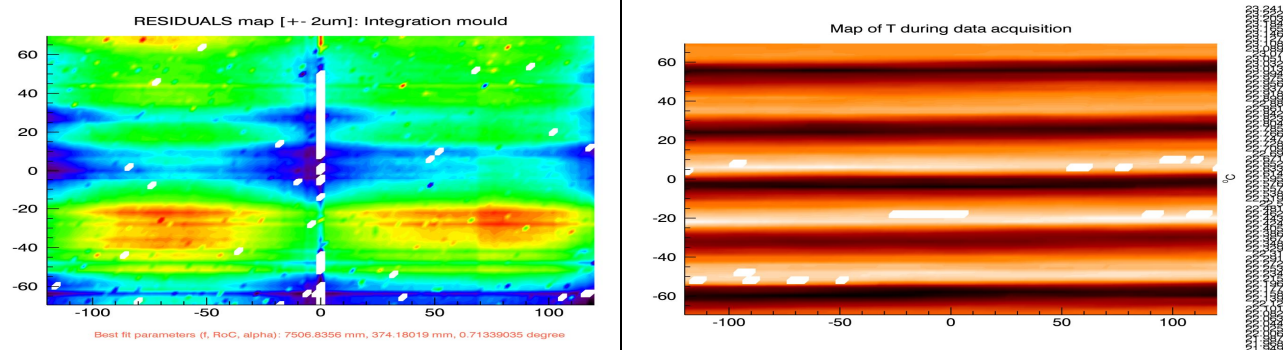


Fig. 3: (Left) Map of residuals of the integration mould as measured with CHRcodile optical sensor on lpkf-3D table. The system is inside a room controlled at $\pm 1^\circ\text{C}$: (Right) The T varied from 22°C to 23.25°C during the 4h long acquisition and its effects still influence the measurement since the correction is not 100% effective. The effect is along the azimuthal direction and does not influence the evaluation of the most critical longitudinal profiles.

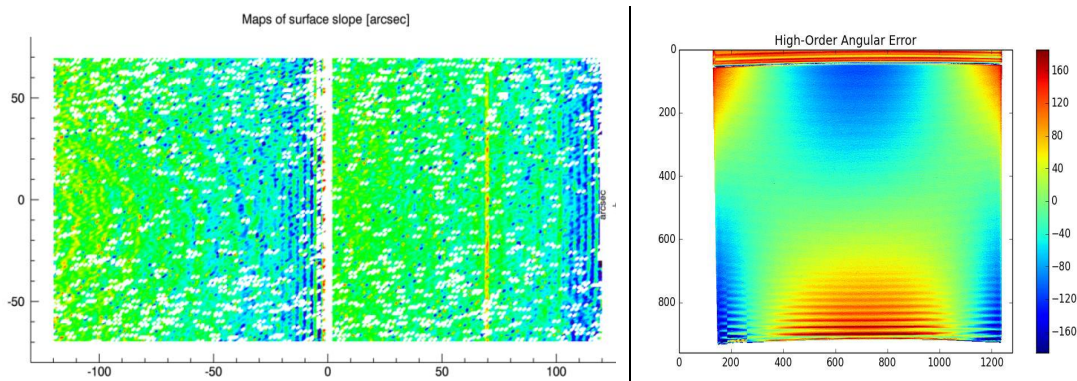


Fig. 4: (Left) Slopes in the residuals map of the integration mould produced in Al by diamond turning: The color scale is $\pm 25''$. (Right) Deflectometry metrology of the parabola side confirms the effects of short scale waviness in the region where machining started, probably coming from machine vibration.

3.2 Integration activities

The integration took place in the OAB laboratory in Merate (Italy), which hosts the IMA, in a clean room controlled in pressure and humidity, with a temperature variation of less than 0.2°C over long periods of time. The activities lasted 2 weeks. All the structural parts have been cleaned with an ultrasonic bath to be compliant with the cleaning requirements of PANTER. The ribs and the glasses have been cleaned with Amber clean soap specific for glasses and distilled water. As a last cleaning step before integration, the glasses have been wiped with acetone just before they were placed on the integration mould, and the mould itself has been cleaned with alcohol: This allowed to remove any dust grains between

the glass and the mould. Interference fringes and deflectometry data are useful in this phase to check for dust presence and eventually repeat the last step of glass positioning if further cleaning is needed. The IMA movements were set in the software for each ribs and glass layer and checked with a run without glue. After everything was ready and checked, the glue was mixed and centrifuged to remove air bubbles and applied in less than 20 minutes. This was repeated for 10 consecutive days for each part and each layer of JIM.

In order to be compatible with the JIM design, the IMA control software has been modified as follows:

- The commands to the autocollimators and the Picomotors were disabled;
- The only active control available was the one working with the linear encoders and the hexapod;
- The control loop was carried up for 6 hours, with checks and corrections operated each 15 minutes.

These changes were required because of the different configuration of JIM with respect to all the other previous prototypes: The main difference was the employment of a monolithic integration mould instead of two. The integration procedure was smoothly operated for all the glass and ribs layers: figure 5 shows the last step of integration, when layer 5 was glued on the JIM prototype.

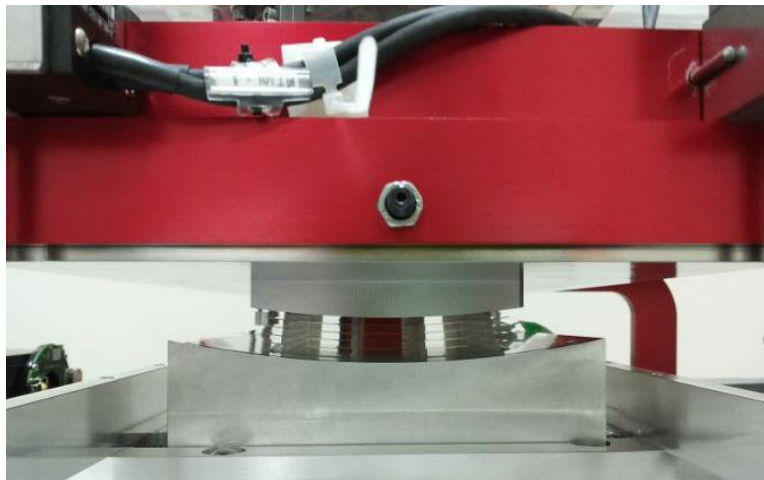


Fig. 5: Stacking of the last layer L5. From the bottom of image we can clearly see: the integration mould, the stacking of 5 layers with their respective ribs, the backplane structure, and a part of the IMA.

4 EXPECTATIONS BASED ON OPTICAL METROLOGY AND FEA SIMULATIONS

All the layers have been optically and X-ray characterized before their integration. The optical characterization is realized with CHRcodile optical sensor mounted on lpkf 3D table at MPE: by scanning the entire glass surface in longitudinal and azimuthal direction, a cloud of points is collected, whose analyses allow to derive the profile shape of the optical surface of the mirror segments. The comparison of this shape with the shape of the slumping mould gives indication on the goodness of the process. Currently, the glass replicate well the waviness content of the mould that account for around 70" HEW. There is also a long wavelength and radius of curvature error in the slumped glasses, derived by thermal effects during the forming process: this is not considered critical since it is a systematic error that repeats always equally for the same slumping parameters and so can be easily accounted for. The estimation of HEW for JIM glasses based on optical metrology ranges from 69" to 80". The X-ray characterization was realized in PANTER. For the purpose, the glasses have been temporarily integrated in a very simple structure with the only aim to hold them in vertical position without introducing significant deformation other than the action of gravity, as shown in figure 6: The effect of gravity itself in this configuration is negligible, contributing less than 1" to the HEW. The measure was considered as reference for the free-standing glasses, to be compared with the values after the integration with ribs. The PANTER data confirmed the expectations from optical metrology down to a range of $\pm 10''$ (see following section 7 for further details).

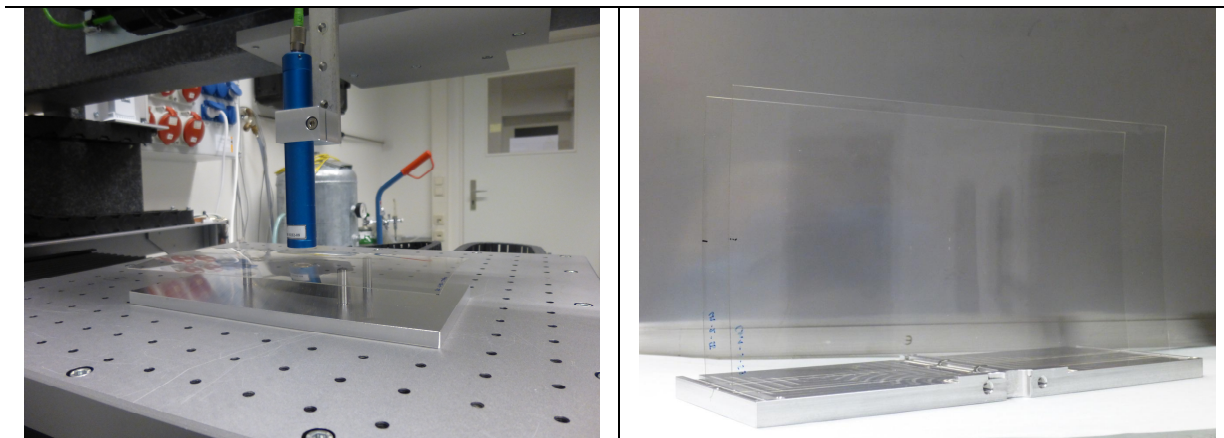


Fig. 6: (Left) Set up for the optical metrology of slumped glasses with CHrocodile optical sensor on lpkf 3D table. (Right): Set up of the free-standing glass characterization in X-ray: The glasses are hold in vertical position only from a single glued point at kink.

The collected data have been employed to simulate by FEA the expected results after integration with ribs. The simulation was carried out for different cases, taking into account the real integration mould or an ideal one, and considering or not the glass thickness variations. The thickness variation of each glass foils plays a role for the result of the indirect slumping: It is estimated that the typical thickness variation of the D263 glasses contribute on average roughly up to 15" to the HEW value [16]. This is not so critical at the moment since the major contribution of glass residuals comes from the mould: However, it has to be taken into account for the future. At MPE a quick and easy thickness measurement method, using double beam interference of sodium light, has been implemented [17]. The thickness variations should be used to simulate the behaviour of the glass during indirect integration most realistically.

The data input for the simulation consists of:

- Optical surface w.r.t reference Wolter I shape
- Back surface w.r.t optical surface (i.e. Thickness variations)
- Mould surface w.r.t reference Wolter I shape
- Position and size of the ribs

Based on this input, the FEM solver calculates the post correction shape of the optical surface. In more details, this is done by calculating the difference between mirror back-surface and integration mould at the rib positions. These values are then applied as boundary conditions to a FEM model of the ideal mirror. The resulting deformation field of the whole mirror is subtracted from the shape error field of the optical surface as measured, resulting in the post correction error which can be used for performance analysis. In general, we obtained HEW expectation of around 60"-65".

5 JIM X-RAY TESTS @ PANTER

JIM was tested in X-ray at the PANTER facility of MPE [18]. A new jig was produced to hold the prototype in vertical position, as shown in figure 7. A two-mask system was realized to allow for pencil beam scan both in azimuthal and longitudinal direction with windows 2 mm wide.

During the positioning in the PANTER, a rough alignment was obtained by using a laser beam which defines the test chamber geometric axis. The recognition of the double reflected laser on the detector indicated that the optics was roughly aligned (right incidence angle). This was followed by a final alignment in X-ray once the vacuum was set by maximizing the incoming intensity on the detector. The focus position was determined by comparing the intra and extra focal images and selecting the position that maximizes symmetric effects. Different segments showed different focus positions of several cm in the free-standing configuration, while the focus position was the same for all the layers of the JIM prototype. Figure 7-right shows the image obtained with the full illumination of JIM: the five single foci of the parallel layers lie on a line at the expected distance given by the ribs height. This proves the correct and precise functioning of the IMA for the integration of X-ray mirror segments.

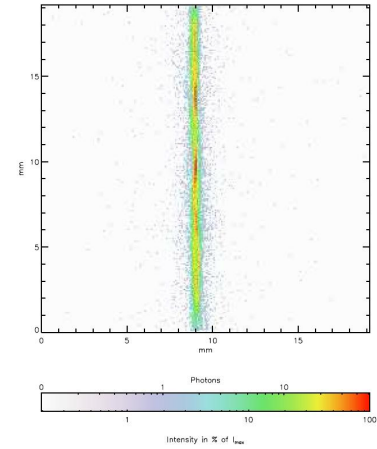
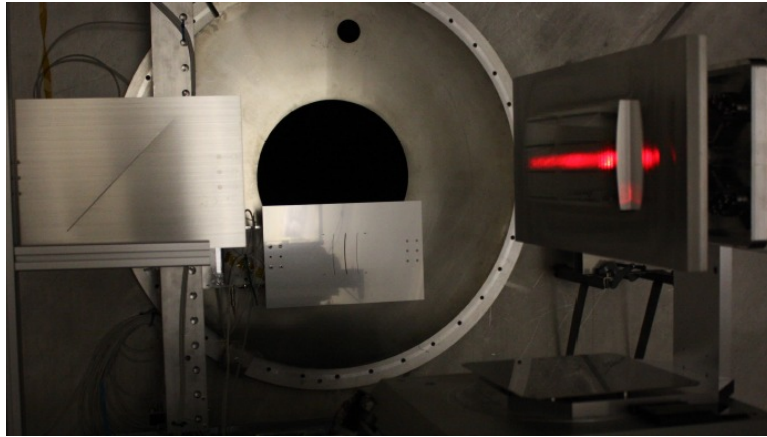


Fig. 7: (Left) JIM mounted inside PANTER X-ray test facility. A laser beam, used for its preliminary analysis before evacuating the PANTER chamber is visible on the glasses. On the left of the picture, the two aluminum plates with slits are the masks used for pencil beam scans. (Right) Full illumination of the entire JIM module: It can be seen that the shells are well aligned one to each other, however their quality is not good enough to clearly separate each single focus.

6 JIM VIBRATION TESTS

Vibration tests up to 50g have been conducted on JIM, in the three main directions. The module survived all the tests without damage. Even if the prototype is not yet in the flight module configuration (mainly because of the larger backplane), this result is an important step forward to confirm the goodness of glass modules for X-ray telescopes manufacturing. These tests were realized recently (July 2015) and the analyses of acquired data is currently under evaluation.

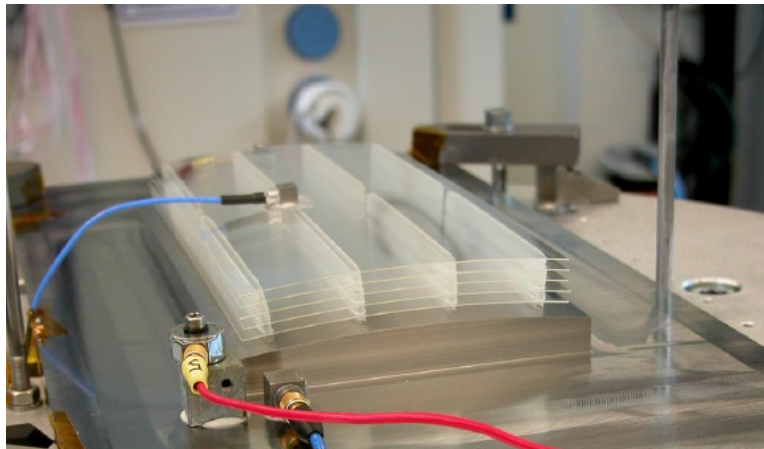


Fig. 8: JIM on the vibration table at MPE laboratory.

7 ANALYSIS OF THE RESULTS

All collected data can be summarized in plots like the one reported in figure 9. Only the plot related to the last layer number 5 is shown since the ones of other layers looks qualitatively the same. The plot shows different lines, coming from metrology or simulations. In particular, the darker solid line represents the data derived from pencil beam measurement carried out in PANTER. It shows in general how, as expected, the major effect of correction is obtained in the proximity of the ribs. The dot and dashed lines represent the results from simulations carried out starting from lpkf 3D data and considering different conditions for the FEA simulations, i.e. taking into account the real thickness variations profiles for the glass or considering the ideal case of constant thickness throughout the whole glass surface; considering the real metrology of mould surface with its residuals or only its ideal nominal shape; and a combination of these cases. The intermediate-color lpkf-reference solid line refers to the pencil beam estimation as derived with the

delta50 method by lpkf data of the glass laying in horizontal position once the gravity effects are subtracted from metrology; while the lighter curved named PANTER-reference line refers to measurement derived with the glass in the free-standing vertical position. A number of general observations can be drawn: in general, the simulation underestimates the slope errors between the ribs. It is up to now not fully understood where this effect comes from. On the other hand the full simulation overestimates the error directly in the vicinity of the rib. We have evidence that this effect can clearly be attributed to noise in the thickness measurements. That is related to the fact that the roughness of the glass back surface is degraded by the contact with the mould during the slumping and this affects the acquisition of thickness data with CHRcodile sensor, making them quite noisy. In general, the overall shape of the measured curve is derived by simulation: However, there are still single features that are not completely understood yet. Deeper analyses are being carried out to improve the results of simulation: They concentrate mainly on the optical metrology data acquisition and analyses and on the understanding of the sensitivity of the FEM simulations to them.

Table 2: Summary of the results for JIM layers in terms of HEW as evaluated from optical metrology or FEM simulations compared to the actual values obtained by X-ray PANTER tests.

Layer	Glass name*	HEW _{optical}	HEW _{PANTER-free}	HEW _{integ.-sim}	HEW _{PANTER-ribs}
L1	CM1 M1 59	80	n.a.	61	68.7
L2	CM1 18 03	69	81.5	64	71.7
L3	CM1 21 14	75	82.8	65	62.3
L4	CM1 17 25	75	70.5	62	61.8
L5	CM1 14 39	72	64.1	60	66.3

* Slumped glasses are named CM1-xx-yy where CM1 indicate the used Ceramics Mould #1; xx is the consecutive no. of slumping process on that mould; yy is a sequential number for the glass foils as delivered by the manufacturer. The glass for layer L1 was slumped making use of a muffle, therefore the letter M in its name.

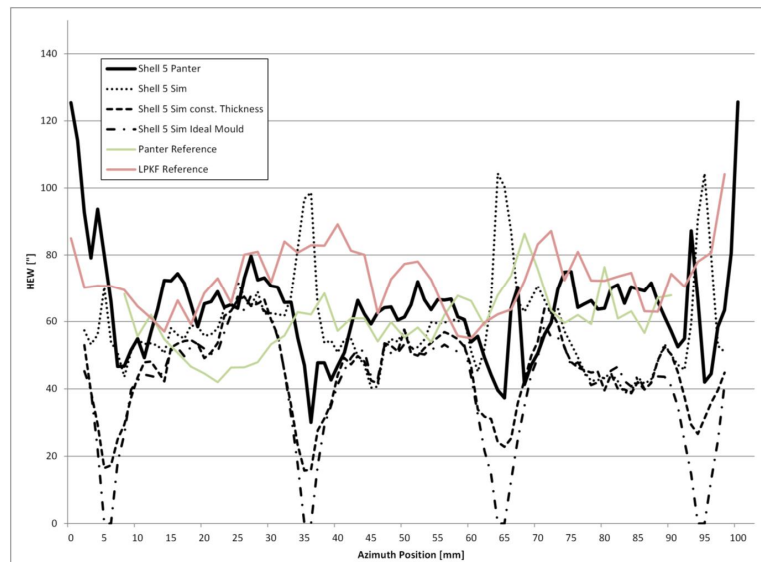


Fig. 9: Comparison of PANTER and simulation data for JIM layer L5: the plots look qualitatively the same for the other layers. See the text for major explanation on the different curves.

7.1 Summary and future plans

Despite of the results in terms of HEW number not looking very good, the activities presented in this paper have been of valuable importance for the lessons they taught:

- The production of AI integration moulds by diamond turning is an easier-cheaper-faster alternative for mould integration that is worth further exploration. It was demonstrated that values of around 10" HEW (in single

reflection) are easily reachable. Activities are currently planned to further improve the result, mainly reducing the waviness at the beginning of the machined area probably coming from vibrations;

- The INAF-OAB integration process works well also in the indirect approach: this was the first time that the integration with IMA was realized with a concave integration mould that guarantees the possibility of inspection and metrology of the optical side of segments during the integration;
- It was confirmed that the current major limitation for MPE slumped segments comes from waviness content at cm scale of the mould that is replicated into the glasses during the slumping process;
- Analysis routines and simulations have been upgraded and further improvements have been individuated to derive more accurate expectations;
- Vibration tests confirmed the goodness of the glass module design to survive loads representative of operative life conditions.

All the above mentioned lessons will be employed for the realization of future prototypes, once better glasses are available.

8 CONCLUSION

This paper describes JIM, a Joint Integrated Module prototype of Segmented Glass X-ray Optical Unit, realized in collaboration by MPE and INAF-OAB: MPE provided the indirect slumped segments of Wolter I X-ray mirror to be integrated into the prototype following the cold slumping approach established by INAF-OAB. The integration took place in the clean laboratory of OAB that hosts the ad-hoc developed Integration Machine. JIM is composed of a stack of 5 equal monolithic layers (parabola and hyperbola side of the Wolter I designed connected together in a single piece), assembled parallel one to each other through glued plane-parallel glass ribs. A backplane holds the stack, providing the necessary rigidity and interface for all the integration and characterization activities. All the layers have been measured optically and in X-ray both before and after the integration: The acquired data have been employed to simulate the expected results in terms of HEW through FEM analyses. In general, the simulation works quite well, even if areas of improvement have been individuated, mainly related to the acquisition of data with CHRcodile sensor on the lpkf table. The current resolution of JIM is around 60"-70": The integration process has been proved to work as expected, however the glasses optical quality is limited by waviness content at cm scale (that cannot be totally corrected during integration) present in the mould and replicated into the segments during the slumping. A better mould, the first step toward an improved future JIM, is expected to be delivered in September. The activities conducted this year have been of valuable importance since they allowed to set up all the procedures and routine simulation and analyses for such prototypes manufacturing and characterization, and also individuate the areas in which they can be further improved. Furthermore, they allowed to demonstrate the use of Aluminum diamond turned integration mould as well as the possibility of indirect integration with IMA.

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