Slumped glass option for making the XEUS mirrors: preliminary design and ongoing developments

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ABSTRACT

The XEUS mission (X-ray Evolving-Universe Spectroscopy Mission) of ESA, in the present configuration has a mirror collecting area in the order of 5-6 m^2 @ 1 keV, 2 m^2 @ 7 keV and 1 m^2 @ 10 keV. These large collecting areas could be obtained with a mirror assembly composed of a large number of high quality segments each being able to deliver the angular resolution requested by the mission or better. The XEUS telescope will fit in the fairing of an Ariane 5 ECA launcher and hence its diameter is presently of about 4.5 m. The request in terms of angular resolution of the telescope has been set to 5 arcsec with a goal of 2 arcsec. Due to the large size of the optics it is impossible to create closed shells like those used for XMM or Chandra and hence it will be necessary to assemble a large number of segments (for example of ~0.6 m x ~0.3 m size) to recreate the mirror shells. These segments will form a module, an optical sub-unit of the telescope. The modules will be assembled to form the whole mirror system. As for all the space missions, the limits imposed on the payload mass budget by the launcher is the main driver that force the use of very lightweight optics and this request is of course very challenging. For example, the current design for XEUS foresees a geometric-area/mass ratio better than about 30 cm^2/kg. In this article is illustrated a possible approach for the realization of large size and lightweight X-ray mirrors that derive from an experience gained from a previous work made in INAF-OAB on the thermal slumping of thin glass optics. The process foresees the use of a mould having a good optical figure but opposite shape respect to the segment to be slumped. On the mould is placed an initially flat glass sheet. With a suitable thermal cycle the glass sheet is conformed to the mould shape. Once tested for acceptance the glass sheet it is then integrated into a module by means of a robotic arm having a feedback system to confirm the correct alignment. A study on different optical geometries using the classical Wolter I and Kirkpatrick-Baez configurations has been also performed to investigate the theoretical performances obtainable with optics made using very thin glass shells.

Keywords: Hot slumping, Mould, Thermal Cycle, Segmented Optics, Glass Slumping, X-ray optics.

1. INTRODUCTION

The present configuration of the ESA mission XEUS(1) will use a single telescope having a diameter of about 4.5 m that fits inside the fairing of the Ariane 5 ECA launcher. The effective area of the telescope is requested to be of 5-6 m^2 @ 1 keV and about 2 m^2 @ 7 keV with an extension in energy up to 30 keV using multilayers coatings deposited onto the inner shells of the optical system. The focal length will be of 35 meters and hence a formation fly approach is foreseen to avoid the need of a mechanical boom linking the optics to the sensors that doesn't guarantee the necessary structural stability to the overall system. The two components will fly in two distinct spacecrafts (Fig.1), one for the optics and the other for the detectors, that will move in formation linked by an active tracking system. This system will ensure that the relative position of the optics respect to the focal plane sensors will stay within a volume of 1 mm^3. Another of the big challenges in this project is to satisfy the imaging resolution required from the science requirements and staying within the weight budget allocated for the optics. Infact, the resolution requested to the optics of XEUS is of 5 arcsec with a goal of 2 arcsec HEW and this must be obtained with a mass budget allocated for the optics of 1200 Kg. This last value bring the ratio geometric-area/mass better than a value of about 30 cm^2/kg that is very low and imply that the optics

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needs to be very thin, maintaining in the meantime a sufficient stiffness to retain the optical shape and survive to the launch phase.

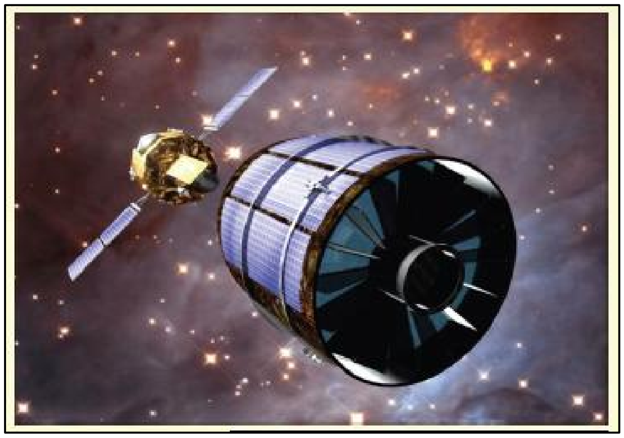

Fig. 1) XEUS Formation Fly

The baseline technology presently under development for the optical payload is the Silicon "Pore Optics"[(2)] that use a technique developed from the know-how of the electronic industry. Using standard silicon wafers, the procedure foresees to produce segments in which are etched few hundreds of microns deep channels having low microroughness. Using a mandrel the wafers are shape formed and aligned in a stack so to form the mirror units that are used to assemble the full telescope.

An alternative technique that is under study for the optics of XEUS is the thermal slumping of glass segments.
This approach offers a number of advantages because:

- Thanks to the increasingly large sizes of LCD TV screens, high quality glass is available at, in practice, any size and thickness (ranging from 50 to 500 μm) with a very good initial surface quality (few Angstroms rms) and low price; On the contrary the Pore Optics are limited by the present day dimensions of the Silicon wafers (300 mm diam.);

- Using the hot slumping it is possible to create true Wolter I profiles with any length and without any limitation due to inherent aberrations. Instead, the two cone approximation used in the Pore Optics has an intrinsic limitation in length to minimize the coma aberration;

- Alternative optical geometries are also possible due to the large focal length. For example, the Kirkpatrick-Baez configuration (K-B) could be of easier implementation than the Wolter I because it foresees the use of flat surfaces having a small bending along the optical path. As a drawback this configuration is less efficient that the Wolter I at high energies due to the larger incidence angle of the photons but the large focal length help to minimize this effect;

- The filling-up of the available geometrical area in a module could be very efficient using thin glass sheets. The area loss can be 20-40 % in total.

Since it is impossible to realize large optics like those for XEUS using closed shells, the glass mirrors will be formed by rectangular segments that, to conform to the mass limitation and geometric area, will have typically a thickness of few hundred microns. Following this approach a number of these glass segments will be mounted in a module and then the modules will be assembled to form the telescope optics. A general problem for the optics is also linked to the fact that the mirrors surface is so huge that the optics can't be thermally controlled. This means that the CTEs of the glass and of the structure holding in position the mirrors must have a very good match so to avoid optical distortions once in orbit and at low temperature. To evaluate correctly the impact that these thermo/mechanical constrains have on the design of the

XEUS optics it is of primary importance to start from some theoretical considerations and to analyze the behavior of simulated optics by means of finite element analysis. It is of course also basilar to individuate among a set of possible materials one or more of them that could be used for the manufacturing of the mirrors substrates and able to fit the high optical and mechanical requirements.
In the following, we describe a possible manufacturing technique currently under investigation and development concerning the use for the optics of very thin glass segments and a preliminary comparison of materials that could be used for the optics and the mould. The status of the investigation on this manufacturing technique is presented as well. Moreover, some possible optical configurations based on the Wolter I and K-B designs are described.

2. SLUMPING OF VERY THIN GLASS OPTICS

The concept of using the hot slumping technique for the production of X ray optical surfaces is under investigation in a number of research centers like for example the NASA/Goddard Space Flight Centre (for the Constellation-X mission). In Europe the technique has been investigated in Reflex firm (Czech Republic), in Germany by the Max Planck Institute (MPE) and in Italy by the INAF-Astronomical Observatory of Brera (INAF-OAB). In Brera, that has a long tradition in the development of X-Ray optics, the slumping has been investigated also for the manufacturing of normal incidence optics. This particular study[3,4] has been financed in the last 2 years by the European Community in the frame of the OPTICON-FP6 for the European Extremely Large Telescope (E-ELT). The aim of this investigation was the development of a technique for the production of thin glass segments for adaptive optics. These optics, able to flex very quickly and change shape, are an essential part of the optical systems of the modern optical ground telescopes and are used to remove the blurring effect of the atmosphere from the images acquired. The results that have been obtained so far from this study are very interesting in terms of optical quality of the surfaces produced and, in our opinion, the same approach could be used to develop an equivalent technique for the manufacturing of very thin X-Ray optics to be used for the XEUS telescope.

The approach developed in INAF-OAB is named "Hot Press Direct Slumping" and foresees the use of a convex ceramic mould having a good microroughness and acting essentially as a "master". In this approach the optical surface of the glass sheet is placed in contact with the mould and pressed actively, with an uniform pressure, against it during a part of the thermal cycle in which the glass is plastic and can change its shape permanently. This procedure is the opposite of the so called "Indirect Slumping"[5] in which the glass sheet is placed above a concave mould with its optical surface upward, not in contact with the mould surface. This strategy has the advantage that the microroughness of the optical surface is not affected by that of the mould and hence the latter can have a surface finishing less demanding. There is anyway a disadvantage in this approach because the glass sheets commercially available have thickness variations of ten microns or more along the expected sizes necessaries for the XEUS segments. These thickness variations are of course transmitted to the optical surface during the indirect slumping changing the final shape of the surface. A solution to this problem could be the grinding/lapping of the segments (front and rear) before the slumping, so to obtain an uniform thickness of the glass. This problem was also faced in INAF-OAB during the study for the adaptive optic prototype because also in this case (even if for other reasons) there are thickness variation constrains. The solution pursued was essentially the same, grinding and lapping on both the glass surfaces. In this case the thickness of the glass was of about 1.6 mm, much more (in comparison) than the few hundred of microns foreseen for the thickness of the XEUS segments. It is not clear if the small glass thickness could create problems during the grinding/lapping process (i.e. the glass could be easily cracked) and hence this aspect will need to be addressed adequately when using the indirect slumping approach. Of course in the Hot Press Direct Slumping the thickness variations of the glass sheet are not an issue.

The study undertaken by INAF-OAB for E-ELT has the aim to produce a demonstrative 50 cm diam. concave spherical mirror in Borofloat33 glass, with a radius of 5 meters and thickness of 1.6 mm. Even if the thickness of the glass used in this study is very likely too large for the application in the field of the x-ray optics for XEUS, the investigation has permitted to INAF-OAB to gain precious experience and to put the "hands" on the slumping technique and on the related problems. This experience of course can be now applied for the specific problems related to the manufacturing of the segments necessaries for the assembly of the mirrors of XEUS. A number of results have been already obtained that give confidence that the approach till here developed is viable and that there are no obvious showstoppers.
Here we briefly review some of the results obtained during the past two years for the E-ELT study. In Fig. 2 is shown a slumped Borofloat 33 glass segment having a diameter of 130 mm placed onto a spherical convex mould made in

Zerodur K20[6], having a radius of curvature of 4000 mm. As visible, the pattern of interference fringes generated from sodium light that depict the shape difference between mould and glass is quite circular and regular that means that no high spatial frequencies are present. Also, almost no dust was trapped between glass and mould.
In Fig. 3 instead is shown an interferometric measure of the same slumped segment on a diameter of 80 mm that gave a residual error respect to a sphere of 57 nm rms. This means that the optical surface that was slumped had a quality of $\lambda/11$. On the overall size of 130 mm the optical quality was $\lambda/3$.
In all the segments slumped was visible a pattern of features that repeat itself with a good approximation indicating that the opposite of this pattern is very likely also present on the small mould used for these tests. The results till here obtained with this mould are limited from the optical quality of the mould surface and not from the slumped segments, that limit themselves to copy its surface.

Fig. 2) Borofloat glass disk on K20 Mould

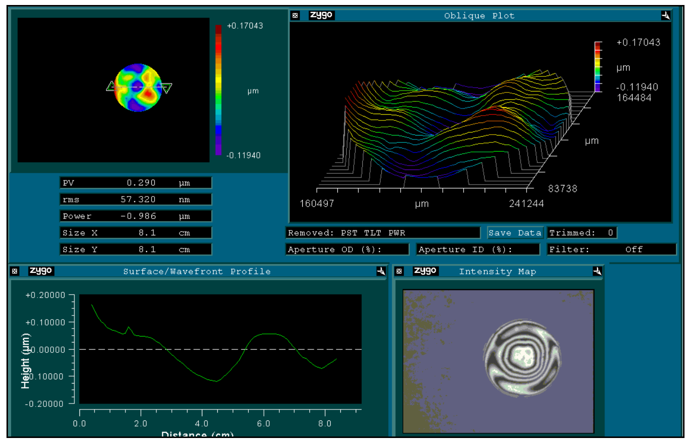

Fig. 3) Interferometric measure of the slumped segment

Recently we have started to use a larger mould having a diameter of 700 mm to prove the scalability of the process. In Fig. 4 is visible the K20 mould just received from SESO meanwhile in Fig. 5 a glass segment of 500 mm diameter is placed onto this mould after the slumping. Again, a pattern of circular fringes was visible, even if not extended up to the edge of the glass. Nevertheless, on the majority of the surface it is possible to count only about 10 fringes that translate in a shape difference between glass and mould of about 3 µm. From this it can be estimated a profile error of no more than 2.5 arcsec. We are improving the optimization of the scaled-up process to further push the performances obtainable, but this preliminary result on a large glass disk (having a size comparable to that foreseen for XEUS segment) is quite promising in view of the high performances needed for the XEUS optics.

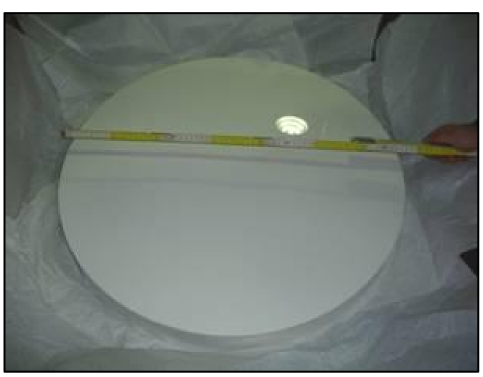

Fig. 4) 700 mm diameter K20 Mould

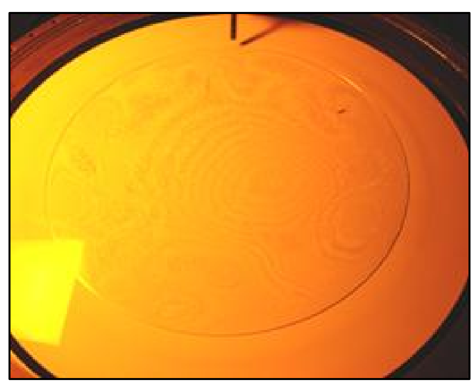

Fig. 5) Fringes between glass and mould

3. COMPARISON BETWEEN DIFFERENT MOULD AND GLASS MATERIALS

A consideration that must be kept in mind is that the choice of a mould material cannot be driven only by terms as simple as the thermo-mechanical material properties. The end product is the result of a process, which may affect or be affected by the substrate properties. The process control is, indeed, an integral part of the fabrication, and virtually every step, starting with considerations about the procurement of the raw material for the blank and ending with the certification of the finished component, must be considered also part of the selection process. All these considerations must be properly weighted in a merit function to reach an acceptable trade-off between the many input parameters in the effort to choose the best material for the mould. During the E-ELT study, we tested a number of materials for the selection of the mould, choosing the Zerodur K20. Instead, for the slumping of the segments of XEUS we think that it is better to switch to another material like the Silicon Carbide. Different types of SiC can be produced with a range of values in the properties. A number of characteristics are quantitatively compared with the K20 in Tab. 1 and summarized in the following list:

- It has a thermal conductivity that is very high, comparable to that of a metal (short thermal cycle)
- It can be superpolished (with a SiC-CVD cladding) up to 3-5 Å.
- Its hardness is an advantage because it is very unlikely to scratch its surface once finished.
- Its hardness is also a disadvantage during the grinding and figuring of the mould.
- The specific rigidity (Elastic modulus/density) is very high ensuring a stable optical shape under a load

Property	SiC	Zerodur K20
Elastic Modulus (GPa)	**213-476**	**83**
Knoop Hardness (HK 0.1/20)	**2500-3500**	**620**
CTE(RT÷400°C) (1/K x 10-6)	**2.2 - 4.5**	**2.0**
CTE homogeneity	**Good Δ=0.01*10-6K-1**	**Very good Δ=0.004*10-6K-1**
Thermal Conduct. (W/mK)	**102 - 300**	**1.60**
Density (g/cc)	**2.5 - 3.21**	**2.53**
Glass adhesion	**YES**	**NO**
Microroughness	**3 - 20 Å**	**20-30 Å**

TAB. 1) Comparison between SiC and K20

3.1 SiC-Glass adhesion

It worth to note that the SiC has the big disadvantage that at the slumping temperature (about 650 °C) it sticks to the glass. This problem arise because there are always some free Silica atoms on the SiC surface that can be oxidized to SiO_2 during the thermal cycle in presence of Oxygen. Of course the SiO_2 can bind very easily to the glass segment and hence the glass can stick to the surface, forcing the use of some kind of an antisticking layer. What we have tested is the use of a Platinum layer to avoid this. In this test (see Fig. 6) a square piece 1.6 mm thick of Borofloat glass was covered with 40 nm of Platinum. The adhesion of the Pt onto the glass was at this stage quite poor, infact it was possible to remove the material by use of an adhesive tape. The Pt coated glass was placed onto a SiC disk (having a cladding of SiC-CVD) and a microroughness of about 28-30 Å (it was not superpolished). Using a process under vacuum, a thermal cycle was applied having a top temperature of 630 °C. During the cycle it was applied a uniform pressure of about 200 gr/cm^2. At the end, the glass was in a very tight contact with the mould and a blast of compressed air was necessary to separate the two pieces, leaving the Platinum layer adherent to the glass.

The use of a Platinum layer deposited onto the glass before the slumping offer a number of advantages:

- The Pt act as a release agent for mould separation: this is a critical aspect of the procedure that permit the use of the SiC as mould material.
- The Pt act as X-ray reflecting coating (like gold for the electroforming replica process): this avoid to coat with a reflecting coating the segment after the slumping.
- The thermal cycle enhance the Pt adhesion on the glass: after the thermal cycle it was no longer possible to remove the Platinum with an adhesive tape.
- The stresses of the Pt on the glass are relaxed: it is well known that a coating layer introduce stresses in the substrate, an important issue to be kept in mind in the case of very thin substrates.

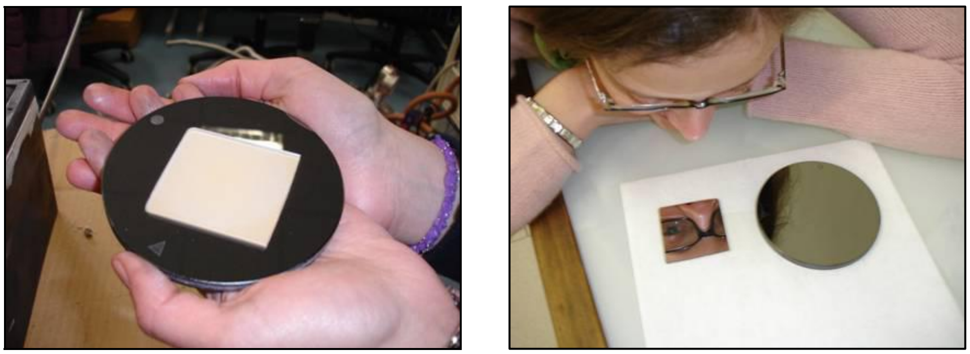

Fig. 6 Antisticking test using a SiC mould with a Pt coated Borofloat glass

The SiC offers also a CTE similar to a number of very thin glass sheets commercially available (see Tab 2) that are produced by means of a fusion draw process.

3.2 Thin glass foils

The Thin, Ultra Thin and MicroSheets Glass segments that are present on the market are produced by Schott, Corning and Pilkington. These panels are typically used in the LCD industry for the flat panel displays. For this reason it is possible to purchase these segments also in large sizes (of the order of a meter). A search on Internet has produced the types of glass shown in Table 2. Five of them have a CTE that is around 4, with a good matching of the CTE to that of the Silicon Carbide. They are the AF32, AF37, AF45, 1737F, Eagle2000. We foresee to start an investigation on some of these type of glasses to find the best match with the SiC mould.

	SCHOTT				CORNING		
	AF32	**AF37**	**AF45**	**D263T**	**0211**	**1737F**	**Aegle2000**
Density (g/cm3)	**2.43**	**2.48**	**2.72**	**2.51**	**2.53**	**2.54**	**2.37**
Young Mod.(kN/mm2)	**n.a.**	**78**	**66**	**72.9**	**75.9**	**71.4**	**70.9**
CTE(10-6/K/m)	**3.2**	**3.77**	**4.5**	**7.2**	**7.38**	**4.2**	**3.6**
Strain point (C°)	**n.a.**	**684**	**627**	**529**	**508**	**666**	**669**
Available thickness(mm)	**0.1-1.1**	**0.7**	**0.05-1.1**	**0.03-1.1**	**0.05-0. 5**	**0.5-1.1**	**0.5-0.7**
Thickness const.(mm)	**+/-0.005**	**+/-0.05**	**+/-0.01-0.05**	**+/-0.008-0.5**	**n.a.**	**n.a.**	**+/-0.02**
Dimens.(mm)	**440x360**	**2160x2400**	**440x360**	**440x360**	**440x430**	**355x457**	**1100x1250**

TAB. 2 Thin glass foils types

In the next section are presented the two key steps that could be used for the slumping of very thin glass sheets and for their integration into a module of XEUS. The first step derive from the experience obtained from the E-ELT study while the second one is related to a new integration concept suitable for the assembly of the slumped shells inside the modules of XEUS.

4. HOT PRESS DIRECT SLUMPING AND INTEGRATION FOR XEUS

The proposed approach for the production of the slumped segments is shown in Fig. 7 and consists in the following steps: a convex mould having the complementary shape desired for the optical segment is manufactured in a suitable material that has a CTE as similar as possible to that of the glass to be slumped. The microroughness surface finishing of the mould will be similar to that necessary for the finished slumped segment. This requirement is necessary because the procedure foresees to copy not only the geometry of the mould but also its higher spatial frequencies and in particular a part of its microroughness.

The glass segment to be slumped is initially coated with an antisticking/reflecting layer like Platinum or other x-ray reflecting material. This layer is first of all necessary to avoid the sticking of the glass onto the SiC mould during the slumping as described previously. We have cited here the Silicon Carbide as material for the mould because it is very likely the material of choice for this particular application, due to its thermo-structural properties. The deposition of an antisticking layer could permit in principle also the use of a different kind of material. After a deep cleaning of the two components (in a cleanroom environment) the mould and the flat glass sheet are placed in a muffle, the glass with the Pt layer placed above the mould and in contact with it. The use of a muffle is necessary to ensure a better temperature distribution during the slumping process and it permits also to remove the air so to minimize the convection and to use only the irradiation, with obvious advantages in terms of homogeneous heat distribution. Another advantage in using a muffle arises from the fact that it protects the mould and the glass from the dusty ambient of the oven. The muffle is placed inside the oven and a suitable thermal cycle is then applied with predetermined warming-up, holding times and cooling rates.
In this approach, during the slumping a pressure of 150-200 gr/cm^2 is applied on the glass so to force it against the mould surface. This approach ensures the full contact of the glass against the mould and is also the reason for which it is necessary to manufacture the mould surface with a good microroughness.
At the end of the slumping process the glass sheet will be characterized by means of the measurement of its optical shape using an astatic support and a non contact profilometer. This support is able to remove the gravity induced deformations from the shape of the segment permitting hence to measure it in a near weightless condition. The final product of this step is a thin glass shell having the desired shape and already coated with the reflecting layer for X-Rays. Since this shell is very floppy, it is mandatory to have an adequate handling tool able to maintain its free standing shape during the integration phase

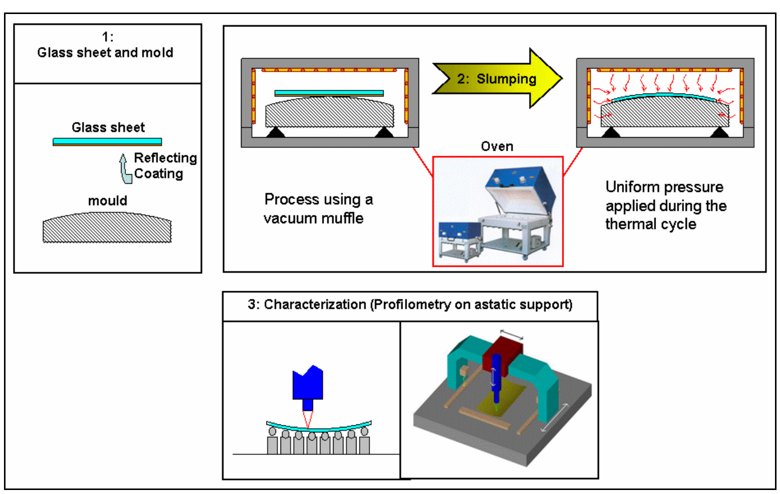

Fig. 7) Slumping step

The integration of the segments in the module is as important as the slumping itself.
In order to save the production costs for the manufacturing of the high precision SiC moulds, it could be possible to use the same mould to produce shells belonging to an interval of radii. This is possible because these shells will have almost the same profiles. Meanwhile, for the integration, it will be necessary to have a dedicated tool for each radius of the shells. We propose to use as integration tool a number of porous graphite chucks, each one having the theoretical geometrical shape of the shell for a specific radius. The porosity of the chuck allow us to use a vacuum suction to maintain the right shape of the segments to be integrated until fixed into the module. This chuck is moved by means of a robotic arm under computer control.
Let us assume that the segment has been slumped and accepted for the integration. Following the Fig. 8, the segment to be integrated is placed on the graphite mould (having the correct shape) and the vacuum suction is activated. Since the segment has been slumped, its shape will be very similar to that of the graphite mould and will have no appreciable subsequent spring-back. A number of ribs, having the same CTE of the glass, will be glued on the back of the segment along all its length (1) to stiff the structure and ensure to fulfil the resonance specs during the launch phase. After the curing of the very low shrinkage glue each segment is integrated by means of a robotic arm, starting from the external ring. In this phase we propose to align the segments in the module using a 3D machine. In a feedback approach, the position data taken from some reference points onto the chuck will be compared with their theoretical predetermined positions. This will ensure that the shell will be in the correct position for the gluing into the module (2). Every segment is glued onto the previous one (except the first that is glued onto a backplane) (3). In this way a stack of segments is grown until the module is complete (4).

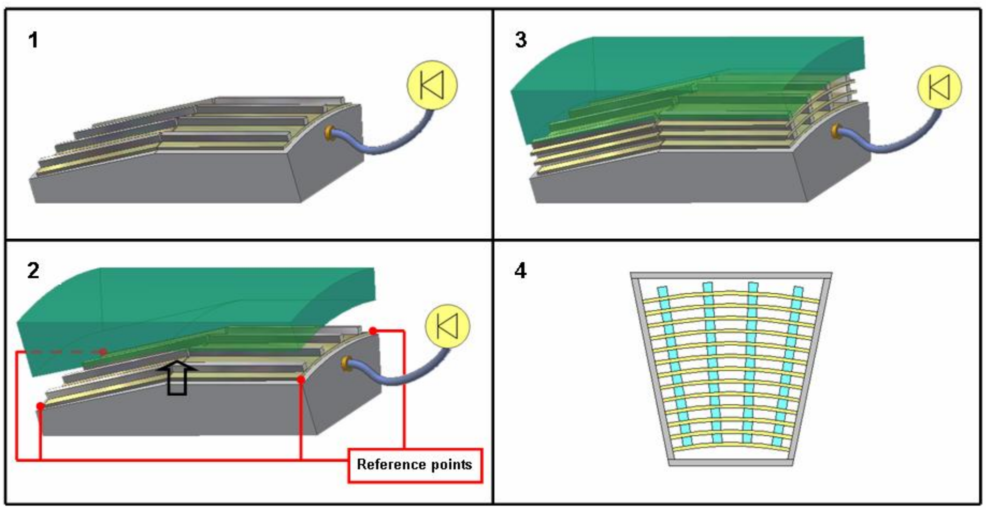

Fig. 8) Integration step

5. NEW CONCEPT OF ASTATIC SUPPORT

One of the problems related to the measure of the “true” shape of very thin slumped segments, as those foreseen for XEUS and having a thickness of some hundredth mm, is the necessity to support adequately the sheets to avoid the distortion under their own weight. The glass sheet under measurement should be essentially free-standing and the support system should not influence its real shape. An astatic support takes care of the gravitational forces acting on the segments, in fact simulating a weightless condition for the segments themselves. Generally, devices of this kind are made of supporting points, three of which are fixed and provide a reference fixed plane, and a number of others that can slide up or down. These points can be preset to apply locally pre-computed forces, obtained with a finite element simulation, that permit to obtain a situation in which the shape of the supported segment is similar to the one it would have without gravity. An example of a FEM simulation of an astatic support made with a total of 9 points (3 fixed + 6 astatic) is shown in Fig. 9. In this case a thick flat glass segment having a size of 100x200 mm and a thickness of 1.1mm is placed onto the support. With this thickness the flatness P-V deviation of the segment is 0.252 μm. We can expect that, for a glass segment having a much lower thickness like that foreseen for XEUS (0.15 mm) the deviations will be about 100 times larger, and hence of the order of 25 μm, making this specific support worthless. It is clear that to reduce this P-V it should be necessary to increase substantially the number of points. This increment of the points (that must be active in the sense that it should be possible to set the pre-computed forces quickly) becomes a factor of complexity and cost. The segments of XEUS that we are investigating have sizes of the order of 300x300 mm, hence an astatic support made as previously described, and useful for the measurement, of very thin glass sheets will have very likely a large number of supporting points making its construction a difficult task.

In INAF-OAB we have developed an alternative design for an astatic support that does not make use of a large number of support points(7). The force that sustains the weight of the glass segment is due to an air cushion and only few support points (for example three) are necessary. The prototype that has been built (and that is here explained) was produced during the study for the slumping of segments for adaptive optics of E-ELT, already mentioned, but a specific implementation for the very thin glass shells of XEUS is quite straightforward. As visible in Fig. 10 and Fig. 11 a circular container having a diameter almost equal to the glass to be measured, contains three load cells placed at 120°. These provide the fixed points on which the glass will come into contact with a predetermined pressure. Also, three movable hard stops are present. Placed along the inner circumference of the container is a magnetic strip having a magnetized zone large few mm. When the circular glass segment is inserted into the circular aperture, it is placed into contact with the hard stops that maintain it at the height of the magnetized zone. In this position the glass edge will face the magnetic strip along all the circumference and a small gap (of 0.5-1 mm) will be present between them. This gap will be filled with a Ferro-fluid liquid that will act like a seal. This fluid is maintained in place thanks to the magnetic strip and does not tend to flow downwards due to its magnetic field. To perform a measurement, air is injected in the bottom cavity until its pressure starts to make the glass to float. The air cannot escape from the bottom cavity due to the Ferro-fluid that closes the gap between the magnetic strip and the glass. At this point, the hard stops are lowered since the glass is suspended on the air cushion. To provide a stable reference plane, the three load cells are lifted toward the glass until their outputs reach predetermined values obtained with a previous FEM analysis. In this configuration, the glass segment shape can be measured in an interferometric way or by means of a profilometer. Even if the segments of XEUS will be rectangular instead of circular, the implementation of a similar device should pose no difficulties because it is possible to implement an analougous rectangular container with magnetic strips.

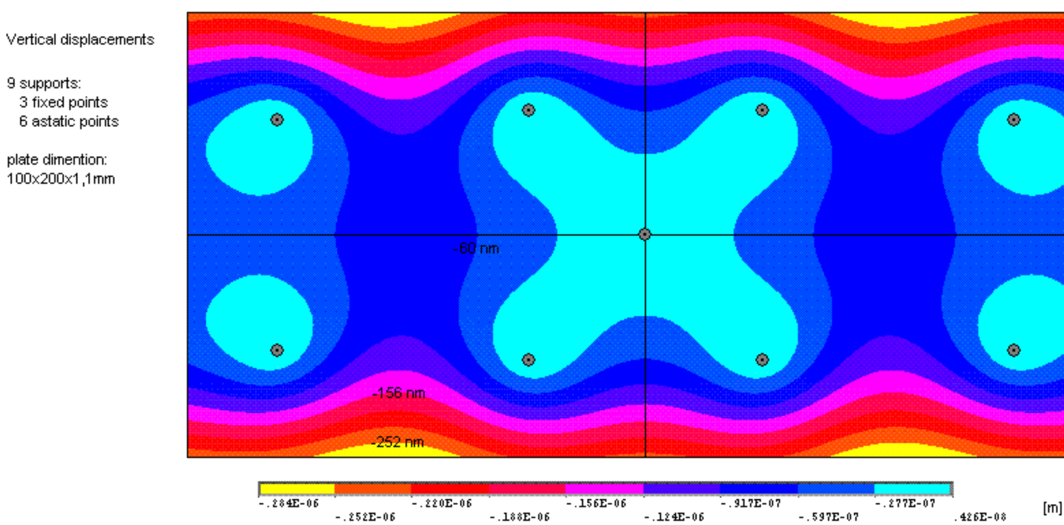

Fig. 9 FEM simulation behavior of a flat Borofloat glass segment (100 x 200 x 1.1 mm) placed onto a standard astatic support having 9 support points

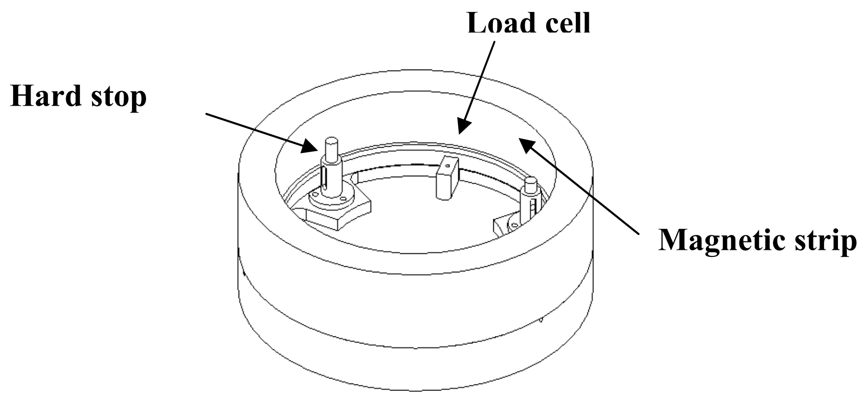

Fig. 10 Astatic support drawing

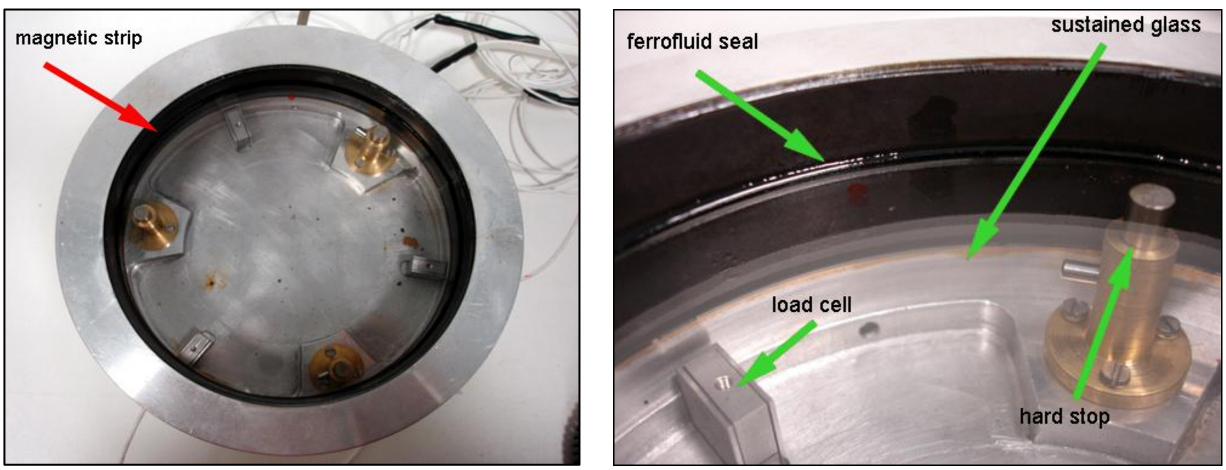

Fig. 11 Astatic support prototype developed for test ing of slumped segments for the adaptive optics study

6. PROPOSED OPTICAL CONFIGURATIONS

Using the specs mentioned in the introduction, we have performed some preliminary analysis considering different optical configurations: the classical Wolter I and the Kirkpatrick-Baez.

4.1 Wolter I configuration

This configuration foresees two double reflection surfaces (parabola + hyperbole) with the segments divided into three rings of modules. The inner ring is composed by 12 modules. The second ring by 24 modules and the external one by 36 modules. All these modules are arranged on a stiff and lightweight supporting structure (see Fig. 12).
The Wolter 1 configuration studied has a focal length of 35m; Parabolas and hyperbolas are 0.6m long (0.3+0.3) and have reinforcing ribs 2 mm wide and placed along the shell length every ~75 mm. The ribs have the function to increase the stiffness of the shells and hence the resonance Eigenfrequencies. This is necessary for the survival of the optics during the launch phase. The resonant frequencies are respectively 182.7 – 183.4 – 183.5 Hz that are high enough to ensure the survival of the optic..

The total number of nested mirror shells is 403, each one built of glass slumped segments with constant thickness of 150 µm. In this preliminary configuration the single module is a box ~ 400 x400 x 600mm. Using this setup, it is possible to achieve an areal density of about 40 cm^2/kg that fulfil the requirement for XEUS baseline. In Tab.3 is shown the distribution of the mirror shells in the rings. Due to the severe operative thermal environment (the mirrors have not an active thermal control) all the modules components and structure are realized by means of the same glass used for the mirror shells, avoiding thermal distortions related to different CTE. Connections between segments and module structure are realized by means of very low shrinkage glue. The module thermal movements and thermal movements of the supporting structure will be decoupled by means of flexures. The weight including the CFRP Structure if of about 2 tons.

Module Ring #	Rmin [mm]	Rmax [mm]	Mirror Shells number
1	610	988	192
2	1130	1508	123
3	1660	2027	88

Tab. 3) Mirror configuration

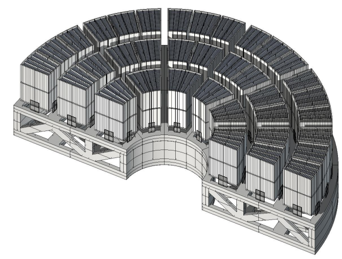

Fig. 12) Modules onto the supporting structure

4.2 Kirkpatrick-Baez configuration

The base configuration of the K-B uses two orthogonal parabolic mirrors to send photons in the focal plane. The mirrors are flat in a direction and parabolic in the other. The photon is focalized initially in x direction and then in y, reaching the focus. This concept is shown in Fig. 13. This design has been already successfully implemented for the LAMAR telescope in a rocket borne mission more than 20 years ago by P. Gorenstein et al.

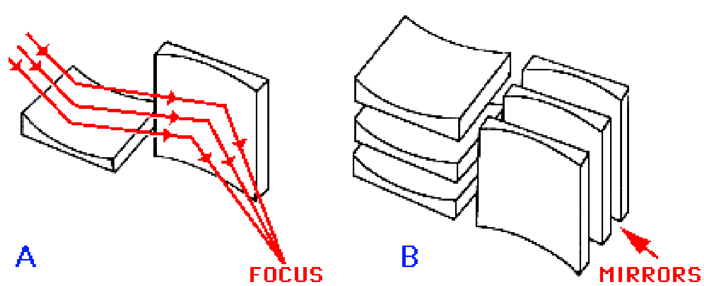

Fig. 13) Concept for Kirkpatrick-Baez configuration

This configuration seems to be very attractive because the bending of the segments along the parabola section is very small (some microns). This enables in principle to shape the glass segments without using a thermal process but just taking advantage of the elasticity of the glass. Following this philosophy it is possible to skip completely the thermal slumping of the segments and use instead directly the integration process already described, with the vacuum chuck shaped for the K-B geometry. Since the bending is so small and also in only one direction, when the glass sheet is released from the vacuum chuck, its spring-back is very small. This philosophy can't be used for the Wolter I geometry because in this case the glass shells must be also strongly curved in a cylindrical fashion and hence the spring back is much larger when the segment is released from the chuck. This approach could be named cold slumping because it is run essentially at room temperature. A big advantage of this methodology is that it permits a fast production of the modules and at a low cost. A disadvantage of the K-B geometry is that, respect to a Wolter I configuration with the same F.L. and aperture, the K-B is less efficient at high energies due to the larger incidence angles (by a factor of two). Also, due to the very long focal length required for the XEUS telescope, the intrinsic coma aberration this geometry is affected by is reduced.

Starting from all these considerations we have investigated two different K-B modules configurations:

- The first configuration is shown in Fig. 14.
The large square fits inside the Arian V fairing and is composed of a number of modules. Each horizontal row is composed by equal modules because they have equal distance from the X axis (like for example the rows marked with the letters A). They focalize the photons on a line along this axis. As long as the distance of the modules from the x axis decrease, the shells inside them change tilt to continue to focalize the photons on the axis. Essentially hence all the modules contribute to send the photons on a line. To obtain a spot in the focal plane of the telescope, another set of modules is placed below the one depicted in Fig. 14. This set is equal to the previous one but rotated of 90 degrees. The effect of this second set of modules is essentially to compress the line into a point in the focus.

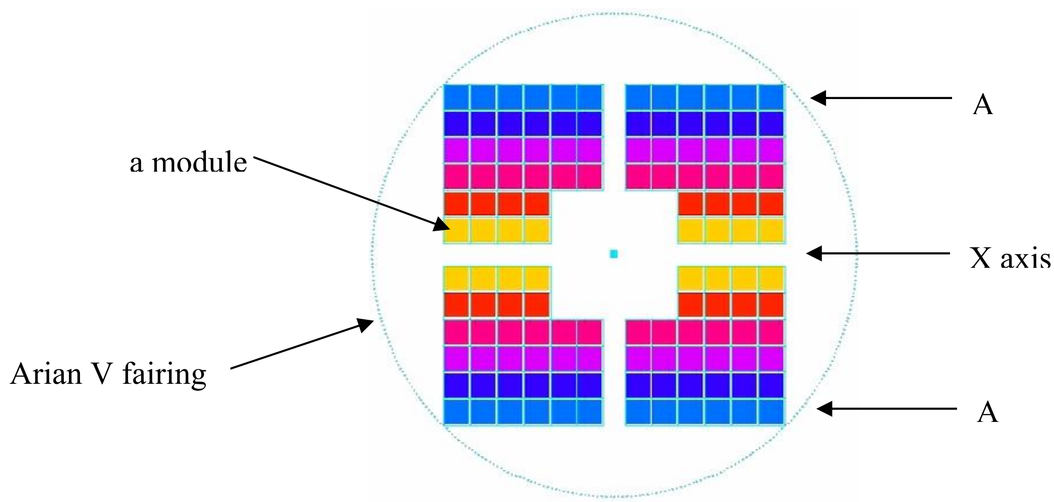

Fig. 14) K-B Configuration 1

This first design exhibits the following features:

- Side length of the entire optic = 3.2 m.
- HEW at 1 KeV 2".1
- Effective Area at 1 KeV = 6.2 m²
- Effective Area at 7 KeV 0.88 m²
- Weight of the mirrors (structure excluded) = 684 Kg
- Number of different modules = 6
- Total number of modules to be produced = 128*2

- The second K-B configuration that has been studied is shown in Fig. 15.

In this case as before the building block is again a module but they are assembled in a different fashion. As visible on the left side of Fig. 15, the modules are assembled in a larger, tie-shaped, structure that we call "petal". The entire telescope optic is build with eight equal petals rotated around the optical axis, as visible on the right side of Fig. 15.
The modules assembled in a petal have all the same sizes and, as before, all those belonging to a row are identical. Below this set of petals is mounted another one. This second set has the building modules rotated at 90 degrees respect to the modules of the first set. Hence, the modules of the second set lying on a given column are identical. With this configuration the areal density is of about 60 cm^2/kg

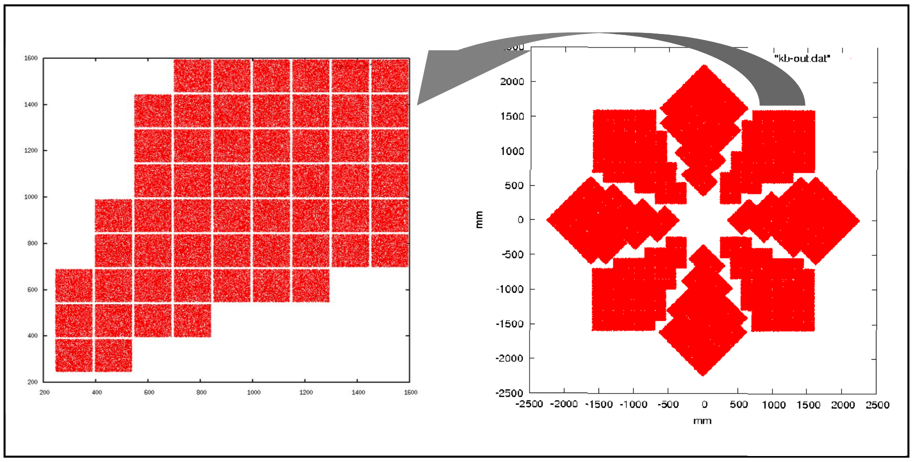

Fig. 15) K-B Configuration 2

This second design exhibits the following features:

- Diameter of the entire optic = 4.5 m.
- HEW at 1 KeV 2”
- Effective Area at 1 KeV = 6 m²
- Effective Area at 7 KeV 1.5 m²
- Weight of the mirrors (structure excluded) < 1000 Kg
- Number of different modules = 9
- Total number of modules to be produced = 56 x 8 x 2 = 896
- Possibility to use a “Cold slumping” approach, Ir/C layer coating

This second configuration is more efficient at high energies than the first because the available space in the centre (near to the optical axis) is filled more efficiently.

7. CONCLUSIONS

In this paper we have described an alternative technology to the “Silicon Pore Optics” based on the glass. The proposed approach makes use of two steps: a first one based on the hot slumping of very thin glass sheets to produce the optical shells segments; the second one is necessary for the integration of the slumped segments. An ongoing work based on the hot slumping technique for adaptive optics developed for the E-ELT telescope has shown interesting results on 1.6 mm thick borofloat glass. In our opinion the know-how gained in this study can be properly adapted for the production of the XEUS optics.

For this particular application we think that the Silicon Carbide is a more appropriate material to be used for the mould (than the Zerodur K20). This material is best suited than the K20 for the production of the slumped segments for XEUS. for a number of reasons. An investigation on the commercially available very thin glass sheets has been done, and a number of these have a CTEs that match quite well that of the SiC. This CTE match helps in the slumping process.

A new concept of astatic support for the measurement of very thin glass segment has been proposed that make use of an air cushion to suspend the glass sheet so to avoid its deformations due to the gravity.

Starting from the XEUS requirements, we have studied a number of optical configurations based on different geometries. In particular a classical Wolter I setup and two different configurations of K-B. There are pro and cons on both the designs, where the Wolter I give a focal spot that is more aberration-free than the K-B, but it is more difficult to be built. On the other hand the Kirkpatrick-Baez is very attractive for its relatively easy implementation, for the lower costs and the fast manufacturing (no thermal cycles). The long focal length of XEUS helps reducing the intrinsic aberration of this last configuration.

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