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Innovative space x-ray telescopes

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INNOVATIVE SPACE X-RAY TELESCOPES

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ABSTRACT

We report on the progress in innovative X-ray mirror development with focus on requirements of future X-ray astronomy space projects. Various future projects in X-ray astronomy and astrophysics will require large light-weight but highly accurate segments with multiple thin shells or foils. The large Wolter 1 grazing incidence multiple mirror arrays, the Kirkpatrick-Baez modules, as well as the large Lobster-Eye X-ray telescope modules in Schmidt arrangement may serve as examples. All these space projects will require high quality and light segmented shells (shaped, bent or flat foils) with high X-ray reflectivity and excellent mechanical stability.

1. INTRODUCTION

The future space X-ray astronomy and astrophysics projects require accurate but light and high throughput multiply nested X-ray optics. There are quite numerous applications requiring the use of innovative and high quality X-ray reflecting foils and flats in X-ray instrumentation including X-ray imaging devices. These applications include the X-ray optics of the Wolter 1 geometry, the X-ray wide field optics of the Lobster-eye geometry, grazing incidence X-ray flat mirrors, bent X-ray mirrors, various X-ray focusing elements, X-ray waveguides, X-ray planar capillaries, etc. They are based either on the replication of flat masters or on other methods of preparation of reflecting foils. The thin X-ray reflecting flats and foils have started to play an increasingly important role in innovative and high sensitivity future experiments in X-ray astrophysics. They have opened a new space for various novel approaches and innovative solutions including those never discussed before.

Perhaps the most important use of innovative X-ray reflecting foils and flats is in the future large aperture and high sensitivity X-ray imaging experiments. The Wolter 1 telescope is proposed to be segmented in the ESA XEUS telescope and analogous space projects, but considerations also exist for large Lobster eye segmented modules, as well as for the segmented Kirkpatrick-Baez systems. The segmentation of the mirror surfaces is extremely important not only for the production of mirror shells, but also for the keeping the weight of large telescopes in a still reasonable limits (Gorenstein, 1998).

2. MATERIALS FOR LARGE SEGMENTED FOIL TELESCOPES

There is growing need for large segmented X-ray foil telescopes of various geometry and geometrical arrangements. This includes the large modules of the Wolter 1 geometry (e.g. assumed for the future ESA X-ray astronomy mission XEUS), the large Kirkpatrick-Baez (further referred as K-B) modules (as they can play an important role in future X-ray astronomy projects as a promising and less laborious to produce alternative) as well as the large Lobster Eye modules in the Schmidt arrangements. Although these particular X-ray optics modules differ in the geometry of foils/shells arrangements, they do not differ much from the point of the view of the foils/shells manufacture and assembly, and also share all the problems of calculations, design, development, weight constraints, manufacture, assembling, testing, etc. It is evident that these problems are common and rather important for majority of the large aperture X-ray astronomy space projects.

We have developed the various prototypes of the above mentioned X-ray optics modules based on high quality X-ray reflecting gold coated float glass foils. The glass represents a promising alternative to recently widely used electroformed nickel shells, the main advantage being much lower specific weight (typically 2.2 g cm^{-3} if compared with 8.8 g cm^{-3} for nickel), however the technology needs to be further exploited and improved in order to achieve the required accuracy. For the large prototype modules of dimensions equal or exceeding 30 x 30 x 30 cm, mostly glass foils of thickness of 0.75 mm have been used for these large modules, although in future this thickness can be further reduced down to 0.3 mm and perhaps even less (we have successfully designed, developed and tested systems based on glass

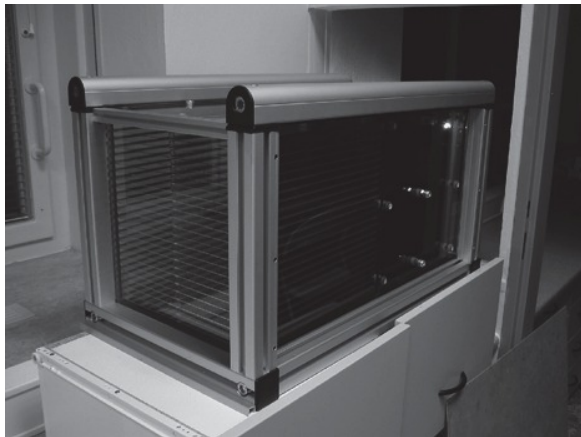foils as thin as 30 microns, albeit for much smaller sizes of the modules).

Figure 1: The large (30 x 30 x 60 cm) LE 2 D module (0.75 mm thick goald coated glass plates). The array can be re-designed and re-shaped to achieve the approximation of a K-B, or alternatively, of a XEUS (i.e. Wolter) geometry, these modules have been also designed and developed.

The requirement of minimizing the weight of future large X-ray space telescopes and at the same time achieving huge collecting areas means that the future large astronomical mirrors are to be based on thin X-ray reflecting foils i.e. thin layers with low weight which can be easily multiply nested to form the precise high throughput systems. Below we discuss some of the analyzed techniques and approaches and related progress.

2.1 Electroformed foils

The electroforming replication technology has been successfully used to develop numerous X-ray optics mirrors for space telescopes (Hudec et al., 2000). This technique has been modified to produce smooth and flat foils from high quality flat masters (Hudec et al., 1991). Although originally developed for the SODART X-ray telescope, this is still a promising alternative technology even for future experiments. The developments have lead to further increase of the thickness uniformity of the foils electroformed from flat masters below 2 % as well as to further improvements of surface quality and other parameters. The common foil material is nickel but alternative materials and alloys are also possible. The additional layers including multilayers can be deposited on the reflecting surface to further improve the reflectivity and energy response.

2.2 Sandwich double-sided foils

Some applications, such as the Schmidt Lobster Eye Optics, require double-sided X-ray reflecting foils. This is a still relatively new approach since all the previous and most of the recent X-ray reflecting foils and flats were one-sided. The innovative techniques to develop such foils have been exploited in the US-Czech Science and Technology Program with promising results (Gorenstein et al., 1996, Inneman et al., 1999).

2.3 Glass foils

The volume density of glass is nearly four times less if compared with electroformed nickel layers. This is why we have carried out an extended study focused on applications of gold-coated glass foils with thickness between 0.03 mm and 1 mm. The glass foils may be used either as flats, or alternatively may be shaped or thermally slumped to achieve the required geometry. In spite of promising inherent properties of glass a lot of work is still waiting to be done in order to mature glass foil technologies to prove their potential and to show successful applications. The glass foils and flats were used e.g. in Lobster Eye X-ray telescope prototypes (with thickness of foils between 0.03 and 0.75 mm and sizes between 3 and 300 mm). The experience learned this way can be preferably applied also for the other types and arrangements of multi-foil X-ray optics.

2.4 Amorphous metals

Although mostly discussed and applied because of their unique magnetic properties, the amorphous (glossy) metals and alloys also exhibit excellent mechanical properties if compared with classical crystalline materials. The results of studies obtained so far (Hudec et al., 2001) indicate that the mechanical stiffness may be nearly 4 times better and hence nearly 4 times improvement may be expected in the weight reduction of the mirror assembly.

On the other hand, the application of this technique in the development of innovative X-ray optics is completely new and needs to be carefully tested and further exploited. From the three available technologies to produce amorphous metal alloys, only one seems to be suitable for X-ray mirror shells (Hudec et al., 2001). We have started study and technology developments in this direction with expected preliminary results in the year 2003.

2.5 Ceramics

The ceramics replication represents a promising alternative to nickel electroforming of X-ray mirror shells and segments (Citterio et al., 2002). The main advantage of the ceramics is a rich variety of suitable materials with volume densities typically between 2.0 and 3.0, and in some cases even less. The method however still needs a substantial effort and improvements (Hudec et al., 2001), especially in the minimizing the internal stresses, in the optimizing the material, and in the application of the reflecting layer. Moreover, there are different alternative methods of ceramics application such as plasma spraying, chemical and physical vapor deposition, which still require careful exploitement to select the optimized technique. The plasma spraying method can be also applied to replicate shells based on various alloys and metals including innovative light materials such as lithium (volume density 0.5).
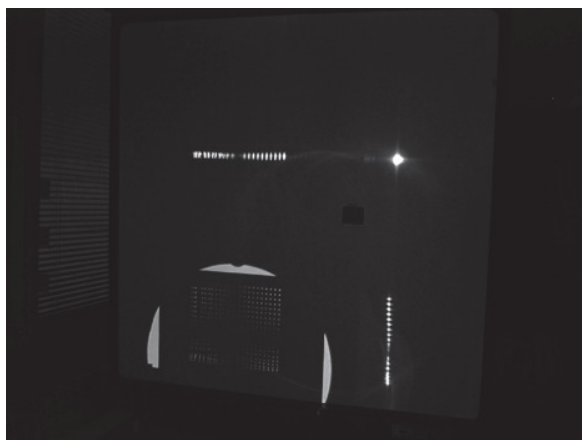

Figure 2: The focal plane image from the large (30 x 30 cm) LE 2 D module (0.75 mm thick glass plates, optical light).

2.6 Glossy carbon

We propose completely new innovative materials such as glossy carbon as possible alternative substrate/material for future large X-ray telescopes like the ESA project XEUS where the severe weight constraints exclude the classical recently widely used technologies and approaches. As far as we know, this material has been never discussed and studied before for this type of application.

The preparation methods of glass-like carbons include thermosetting resins, filler, blending, moulding, polymerisation/curing, machining, carbonisation and graphitisation. The preparation procedure for composite glass-like high-density carbons was developed relatively recently. Additions of filler material are quite effective to suppress shrinkage and also to release readily the evolved gases at the polymerisation and curing stages.

While the preparation of thick, glass-like carbon products is still difficult, the thin layers and films are much easier to be produced. In the thin film glass carbon techniques, the resin is coated on to a silica-glass plate, cured, peeled, and carbonised, and, if necessary, it can be graphitized. It is obvious that this may be considered as one of promising completely new techniques to be exploited as a possible alternative for future large segmented X-ray mirrors/foil telescopes.

The structure of glass-like carbons has been studied over many years. Glass-like carbons are known to be typical, more or less, of isotropic, non-graphitizable carbons. The recent evolutions indicate that the structures of thermosetting resins can be effectively modified to control the structure of resultant glass-like carbon. This way, a glass like carbon with no porosity can be prepared from a chemically hydrophilic thermosetting resin (Marsch et al., 1997).

The glass-like carbons have bulk densities around 1.5 g cm^{-3} (although they can be as small as 1.4 g cm^{-3} and even 0.6 g cm^{-3} if an extended porosity may be accepted) which are almost equal to those of the conventional synthetic graphite and lower than any previous material considered for future large area X-ray mirrors. The glossy carbons with high porosity can even reach bulk densities of 0.6 g cm^{-3}. The bending strength of glass like carbons amounts to 50-200 MPa, the Young's modulus to 20-32 GPa, and the C.T.E. amounts to about 1 x 10^{-6} C^{-1}. Glass like carbons are hard materials as shown by their shore hardness of 100, and of 70-80 after graphitization. However, they have little mechanical shock resistance and belongs to typical fragile materials. This can be, on the other hand, affected by the selection of a suitable filler. They exhibit low self-lubricity and high abrasion resistance reflecting their special structures, compared with conventional graphite.

The applications of glass-like carbons have been rather limited for the past few dozens of years. It is just recently that they have attracted much more interest in terms of industrial applications. Among the parameters, the glass like carbons seems to be favourable because of their low density and low thermal expansion. The large-size composite glass-like carbon thin plates have been already successfully produced for fuel cell separator s (Marsch et al., 1997).

3. X-RAY TELESCOPES BASED ON FOILS AND SHELLS

The following applications require the use of X-ray reflecting foils and flats. Beside high shape accuracy, the large space telescopes require in general large surface areas and hence a low volume density of the used material. This means that the foils must be of low thickness, high mechanical stiffness, and of low volume density.

3.1 Foil telescopes

High throughput high collecting area X-ray telescopes can be formed by shaping of thin foils, mostly in double conical Wolter 1 geometry applications. High quality electroformed Nickel foils have been developed for the SODART space telescope (Hudec et al, 1991) confirming that the electroforming on high quality glass masters can results in high quality smooth (micro roughness typically 1 nm) nickel foils with thickness between 10 microns and 1 mm. Alternative less quality but also of less cost foils e.g. plastic foils, aluminium replicated foils or industrial aluminium foils have been also considered an/or used in space experiments with low requirements for the final angular resolution..

3.2 Lobster Eye telescopes

The Lobster Eye Wide Field X-ray telescopes in Schmidt arrangements are based on perpendicular arrays of double-sided X-ray reflecting flats. In the first prototypes developed and tested, double-sided reflecting flats produced by epoxy sandwich technology as well as gold coated glass foils have been used (Inneman et al., 1999, 2000). Recently, micro Schmidt lobster eye arrays with foils thickness as low as 30 microns have been developed and tested in order to confirm the capability of these systems to achieve fine angular

resolutions of order of a few arc min. The thin foils are separated by 50 microns in these prototypes. On the other hand, large lobster eye systems with Schmidt geometry have been designed and constructed, achieving dimensions up to 30 x 30 x 60 cm. Their optical tests have confirmed the expected performance according to calculations (computer ray-tracing). The X-ray tests of the large LE modules are planned in collaboration with the Max Planck Institute of Extraterrestrial Physik in Garching, Germany at their X-ray test facility Panter in Neuried later this year. The calculations and the measurement results indicate that the lobster eye telescope based on multiarray of modules with thin and closely spaced glass foils (analogous to those already assembled and tested) can meet the requirements e.g. of the ESA ISS Lobster mission (including the angular resolution) and can hence represent an alternative to the recently suggested MCP technique.

3.3 Large segmented Wolter telescopes

The future large space based X-ray telescopes will require extremely large collecting area i.e. very light X-ray optics shells. The highly nested shells of Wolter 1 geometry must be of very low thickness and of low volume density in order to keep the weight of the whole assembly in still reasonable limits. Recently, we have designed and developed a test module array based on 30 x 30 cm glass foil plates 0.75 mm thick and parabolic shape of the surfaces. This module has been designed and constructed to exploit and to test the possible use of shaped glass foils as an alternative for the future ESA X-ray space mission XEUS. The parabolic shape of the particular shells has been obtained by bending of the foils, the alternative technology of thermal shaping of the glass foils is tested recently. X-ray and optical tests are planed for the 2. half of the year 2002.

Module	Size	Plate thickness	Distance	Length	Eff. Angle	Focal length	Resolution	FOV	Energy
	d [mm]	t [mm]	a [mm]	l [mm]	a/l	f [mm]	r [arc min]	[deg]	[keV]
macro	300	0,75	10,80	300	0,036	6000	7	16	3
middle	80	0,30	2,00	80	0,025	400	20	12	2
mini 1	24	0,10	0,30	30	0,010	900	2	5	5
mini 2	24	0,10	0,30	30	0,010	250	6	5	5
micro	3	0,03	0,07	14	0,005	80	4	3	10

Table 1: LE Schmidt modules developed so far

3.4 K-B X-ray telescopes

The large modules of Kirkpatrick-Baez X-ray optics based on multiple and large flats in K-B geometry have been also suggested for future space missions

(Gorenstein, 1998). The K-B modules are based on orthogonal stacks of thin reflectors, each reflector represents a parabola in one dimension.

The modular concepts of Schmidt LE modules, of the large segmented Wolter telescopes (such as XEUS), and of large segmented K-B telescopes are similar: all are based on either planparalel or curved flats and foils. This means that the development of high quality X-ray reflecting foils and flats with high mechanical stiffness and low volume density is extremely important for most of the future X-ray astronomy large aperture projects. The segmented K-B telescopes have the advantage of being highly modular on several levels. All segments are rectangular boxes with the same outer dimensions (Gorenstein, 1998).
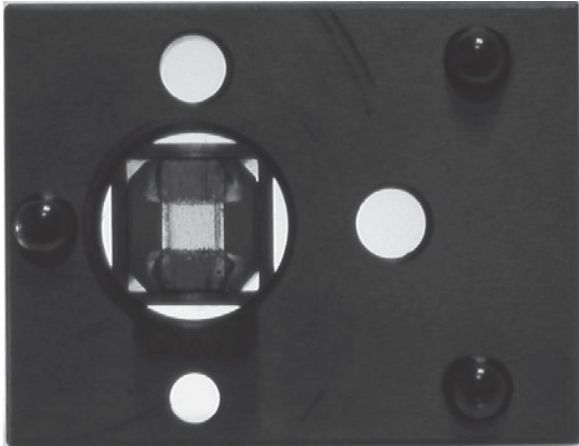
Figure 3: The micro LE Schmidt module (3 x 3 mm, 0.03 mm thick glass foils) in the holder.

4. COMPUTER SIMULATIONS

4.1 General description

To be able to make some estimates on the LE performance, image quality, and scanning observation problems, we have developed a ray-tracing code matching our requirements.

The first version of our software, currently being operational, works with the set of ideally planar surfaces creating a LE optics. The surfaces has a reflectivity depending on the material and its surface quality. Fully 3-D ray-tracing Monte-Carlo simulations are then performed on such a system.

To verify that even such a simple (only planar surfaces) approach can provide us with the valuable results, we have compared the experiment and the simulation of the experiment for the 8 keV photons at point-to-point focusing X-ray LE-like optics. The model fits the

experiment quite well (at least from general point of view).

There is more sophisticated version of the ray-tracing software under development now, which will be able to deal with the curved and distorted surfaces, as well as with the photon scattering on the micro roughness (angle spread function).

4.2 Simulated optics

We have performed a number of various LE designs (varying generally in the foil dimensions and the spacing between the foils). One of the promising designs has 78 mm x 23 mm x 0.1 mm foils and spacing between them 0.3 mm. The focal length is f = 375 mm. We have simulated the Schmidt LE consisting of these foils coated with the gold with the micro roughness $\sigma = 1$ nm.
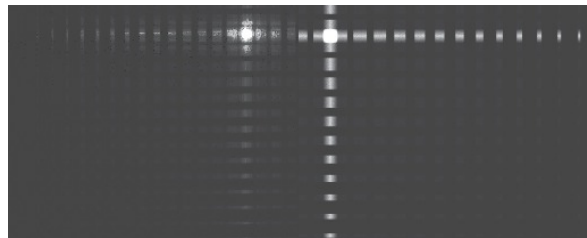

Figure 4: The experiment (left) and the simulation (right) of the 8 keV point-to-point focusing system. The gain defined as a ratio of the maximum value of the pixel and the value of the directly illuminated pixels is ~570 for the experiment and ~600 for the simulation. The FWHM of both peaks is also close to each other. The focal length of the system is f = 1.2 m, the pixel size is 24 μm.(Inneman et al. 2000)

The gain, defined as the ratio of the photons gathered inside the FWHM area with and without optics, ranges from ~ 2500 for softer photons (below 2.5 keV) to just several hundreds for harder photons (2.5 – 10 keV). The gain depends on the FWHM, which will be larger in the reality due to the foil distortions, but gain above ~1000 below 2.5 keV can be expected.

The FWHM of a central peak ranges from 2.5 to 4.5 arc min (270 – 480 μm). For most cases the FWHM was below slightly above 3.0 arc min. For real LE the FWHM will be larger, but comparing the model with the experiment show that the blurring will not be immense.
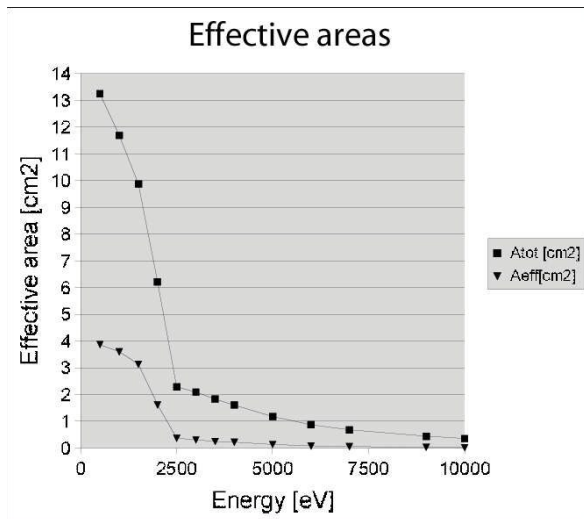
Figure 5: Atot and Aeff for the described optics, please note that the front area of the optics is ~60 cm2.

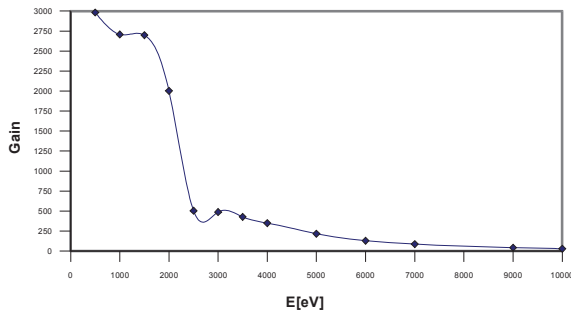*Figure 6: The gain defined as the ratio of the photons gathered inside the FWHM area with and without optic. Simulation of the LE with 78 mm x 23 mm x 0.1 mm foils and 0.3 mm spacing.*

We adopt two definitions of the effective areas (Priedhorsky et al., 1996). First, A_{tot} corresponds with the amount of photons gathered from the single source overall the detector. Second, A_{eff} corresponds with the amount gathered inside the FWHM area. The goal is to minimize A_{tot} while maximizing A_{eff}, e. g. maximize the signal while minimizing the collateral impact on the whole image. A_{eff} is 2-3 cm^2 below 2 keV and ~0.3 cm^2 below 7.5 keV. Atot is ~ 3 times larger.

5. LE ASM DESCRIPTION

The described optics can be used as a soft X-ray All-Sky monitor. The goal is the monitor sensitive in 0.1 – 10.0 keV range, with the limiting flux ~10^{-12} erg/s/cm^2 in soft X-rays per one day, with the angular resolution ~4 arc min and ability to scan almost the all sky several times a day.

The ASM will consist of a number of LE modules. Each module will consist of the optics, and the container. The FOV of such a module is 6 x 6 deg. The dimensions of a module are ~ 10 cm x 10 cm x 40 cm. The weight of each module will be 5-10 kg (1 kg the optics, ~2 kg the detector, 2-5 kg the container). Each module works independently on the other modules.

The detector in each module can remain planar, although the LE focal surface is curved into a sphere. The image distortion caused by the planar detector is very small for the considered optics. The detector will be ~ 4 cm x 4 cm large with the pixel size of ~150 μm. Fast imaging semiconductor detector seems to be the ideal candidate for this job. Just to mention an example, the EPIC-pn camera onboard the ESA XMM-Newton satellite matches most of the requirements for the detector. But faster detectors based on the MOS technology, currently under development, would be better choice.

If 30 modules are aligned side by side, the total FOV of 180 x 6 deg is available. With the main axis perpendicular to the orbit, the ASM will scan the entire sky once per revolution. The modules can be separated into groups or can be mounted onto the hosting body (satellite, ISS...) completely separately. This is useful to avoid the shielding by other parts of the hosting body.
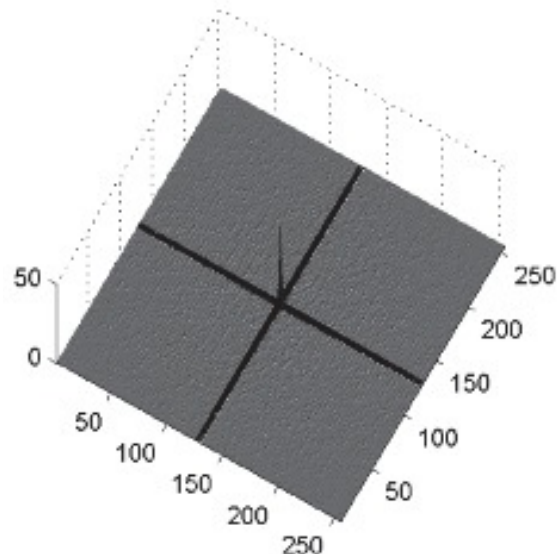

Figure 7: PSF example of the mentioned optics, pixel size scaled to 2px/FWHM

The modularity and module independence provide us with the robustness of the system and decreased development costs. One has to develop and test a single module, while the rest will be completely the same. The in-situ replacement and/or repair (in case of ISS housing) will quite easy.

The average number of events per detector is $\sim 6~s^{-1}$ (scanning observation simulations based on the 1RXS X-ray source catalogue, Voges et al., 1999, and the background model, Priedhorsky et al., 1996). Each event (photon detection, single pixel event) can be described by 34-38 bits (9+9 position, 12 energy, 4-8 time stamp). Overall 230 bits/s has to be transferred per a single module. Together with the telemetry data, ~ 1 kbit/s is a realistic estimate for average data transfer rate per module.
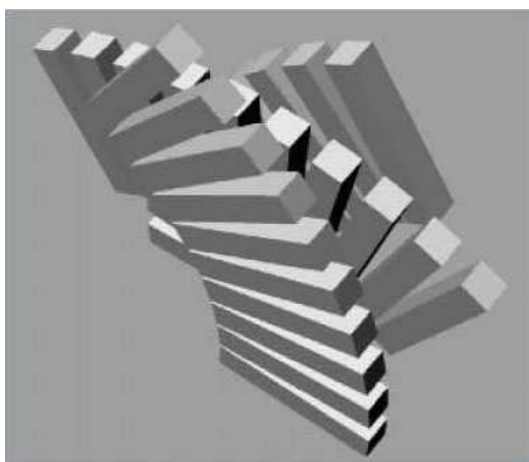

Figure 8: The example of the module arrangement strategy. All three groups of modules are in the parallel planes.

6. MULTILAYER REPLICATION

The additional coatings including the multilayer deposition (including those deposited on mandrels and then replicated to form the reflecting layer on the functional X-ray mirror surface) are expected to play an important role in future X-ray astronomy space missions, as well as in various laboratory applications. One of the main tasks related to future mission and their scientific content and justification is the extension of the range of observation toward the higher energies, perhaps up to 100 keV. These energies are hardly to obtain with classical grazing incidence X-ray optics as for increasing energy the grazing incidence angle decreases resulting in severe decline in collecting area and in efficiency. There are also numerous applications in the

laboratory, especially if there is a need to extend the energy range towards higher energies. The multiplayer replication can be here important in the case of small aperture hollow surfaces where the direct ML application would be difficult and expensive, if not even impossible.

The multilayer flat samples have been successfully replicated using the epoxy replication technology. The tests have confirmed the still good performance of the ML after replication. The replication allows in general to transfer the multilayer structures from mandrels to (mostly inner) surfaces where the direct ML deposition is either difficult to be carried out with the required quality or even impossible.

In the first stage, the flat samples have been replicated and tested. The study continues with replication of layers deposited on rotational symmetric surfaces (mandrels).
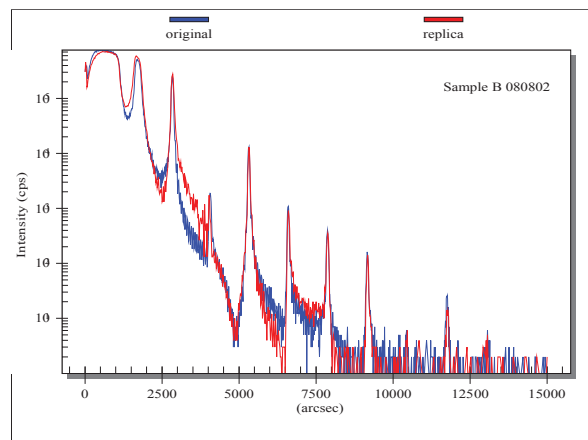

Figure 9: The measured X-ray reflectivity of a multilayer structure - sample B 080802 (20 bilayers Mo/Si) deposited on a glass substrate before (black line) and after replication (red/grey line), logarithmic scale.

The experiment with the Mo/Si ML replication has been carried out in the collaboration of Reflex sro. with Osmic, Inc. The SiO_2 substrates were prepared in the laboratories of the Reflex sro. All the substrates were treated by standard chemical cleaning, ion beam conditioning and plasma cleaning.

Part of the substrates (including substrates B and C mentioned here) were then covered by a special separation layer, while the others (including substrates D and E mentioned in this paper) were not. The substrates

were then sent to the laboratories of Osmic, Inc., where systems of multilayers were deposited. For the test substrate mentioned in this paper, the following multilayers were deposited. On the substrates B and E, the 20 bilayers Mo/Si were deposited, the Mo being the first on the substrate (or on the separation layer). On the substrates C and D, the 20 bilayers Si/Mo have been deposited, Si layer being the first on the substrate (or separation layer). Then the substrates were sent back to the Reflex sro. and the replication technology has been applied resulting in separating the multilayer structure from the substrate. The separation was successful for substrates with separation layer (e.g. B and C mentioned here). On the other hand the test substrates without any separation layer lead to degradation and/or damage inside the multilayer structure.
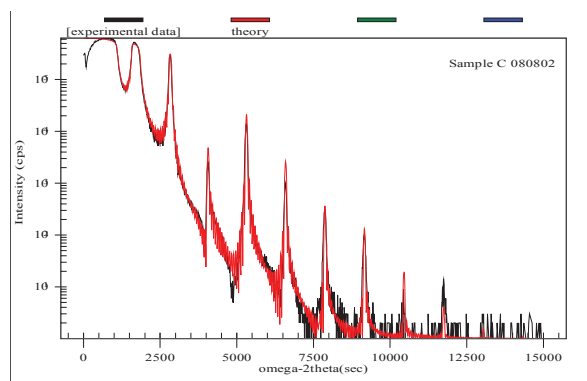

Figure 10: The measured X-ray reflectivity of a multilayer structure - sample C 080802 (20 bilayers Si/Mo) deposited on a glass substrate. Black line - experimental data, red (grey) line – fitted (by Bede REFS software package) data (logarithmic scale).

The results confirm that the multilayers can be successfully replicated i.e. transferred from one surface to the other one. The separation layer must be applied to achieve the necessary high quality of the replication. The replication layer can be exposed to normal atmospheric conditions before the replication process. The material of the first layer on the replication layer (either Si or Mo) has no influence on the quality of the replication. The performance of the multilayer structure before and after the replication process is documented in the Figures X - Y.

More recently, the multilayers deposited on conical rotationally symmetrical master have been successfully replicated to hollow conical test mirror. This is an important step to have multilayers coating also on surfaces where the direct deposition is difficult, especially inside cavities and hollow surfaces.

7. CONCLUSIONS

The recent studies and analyses indicate that there are numerous suitable innovative materials and technologies worth further study for future large aperture X-ray astronomy missions. The production of flat and bent (foils) X-ray optical elements has been confirmed to be reasonably achieved by methods of electroforming and composite replication as an alternative to other methods. These alternatives have been also exploited and include various innovative approaches such as light ceramics replication, plasma spraying, CVD and PVD techniques, glass technologies, glossy metals techniques, as well as glossy carbons. The results obtained with the development of technology for production of large area and high quality one-sided X-ray foils are very promising and together with composite material technologies represent an important input for the development of double-sided flats needed for lobster eye geometries of X-ray optics as well as for others applications.

There is also potential for extending the wide field imaging system to higher energy by the use of multilayer coatings in analogy to those described by Joensen et al., 1994, for flat reflectors in the Kirkpatrick-Baez geometry as well as for some other applications. The related multilayer analyses have been carried out and discussed with resulting directions for further developments and improvements meeting the requirements of the future space missions and other applications.
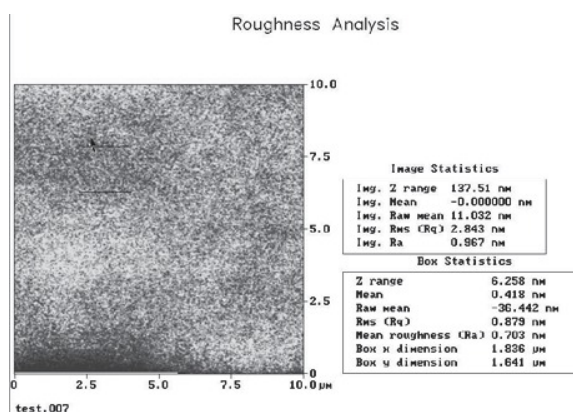

Figure 11: The microroughness measurement of sputtered Mo on flat samples glass foils (Atomic Force Microscope at the Center of Advanced X-ray Technologies, Reflex s.r.o. Prague).

The availability of technologies for development and manufacture of thin X-ray reflecting foils and flats makes the proposals for future large aperture segmented X-ray telescopes with high sensitivity possible. The further studies and developments should focus on exploiting and finding out the preferences and drawbacks of particular alternatives as well as on optimizing the material selection and technology process.

At the same time, the further improvements and developments of testing methods and metrology are unavoidable if the accuracy of the X-ray mirrors is expected to meet the requirements of future X-ray missions.

ACKNOWLEDGEMENTS

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