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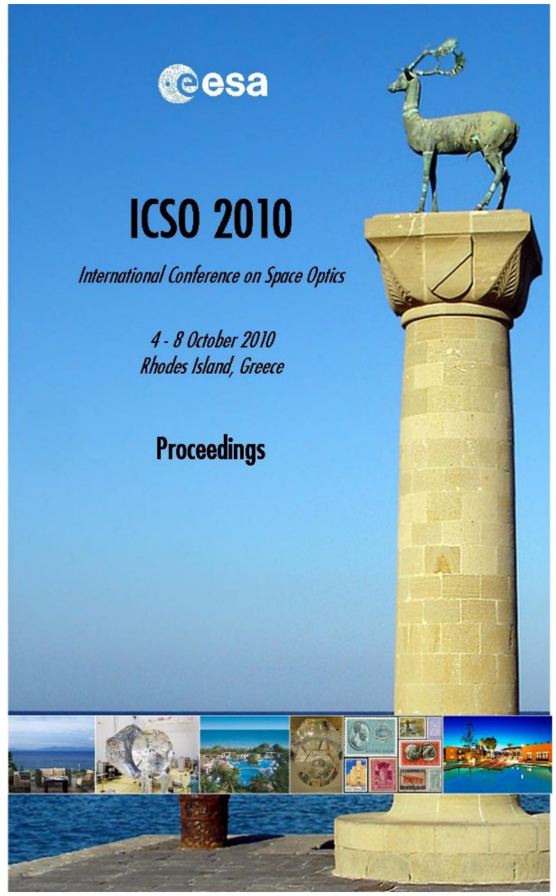

The eROSITA X-ray mirrors: technology and qualification aspects of the production of mandrels, shells and mirror modules

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THE EROSITA X-RAY MIRRORS - TECHNOLOGY AND QUALIFICATION ASPECTS OF THE PRODUCTION OF MANDRELS, SHELLS AND MIRROR MODULES

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I. INTRODUCTION

The name "eROSITA" stands for extended Roentgen Survey with an Imaging Telescope Array. The general design of the eROSITA X-ray telescope is derived from that of ABRIXAS. A bundle of 7 mirror modules with short focal lengths make up a compact telescope which is ideal for survey observations. Similar designs had been proposed for the missions DUO and ROSITA but were not realized due to programmatic shortfall. Compared to those, however, the effective area in the soft X-ray band has now much increased by adding 27 additional outer mirror shells to the original 27 ones of each mirror module. The requirement on the on-axis resolution has also been confined, namely to 15 arc seconds HEW. For these reasons the prefix "extended" was added to the original name "ROSITA". The scientific motivation for this extension is founded in the ambitious goal to detect about 100,000 clusters of galaxies which trace the large scale structure of the Universe in space and time.

The X-ray telescope of eROSITA will consist of 7 identical and co-aligned mirror modules, each with 54 nested Wolter-1 mirror shells. The mirror shells are glued onto a spider wheel which is screwed to the mirror interface structure making a rigid mechanical unit. The assembly of 7 modules forms a compact hexagonal configuration with 1300 mm diameter (see Fig. 1) and will be attached to the telescope structure which connects to the 7 separate CCD cameras in the focal planes. The co-alignment of the mirror module enables eROSITA to perform also pointed observations.

The replication process described in chapter III allows the manufacturing in one single piece and at the same time of both the parabola and hyperbola parts of the Wolter 1 mirror.

II. MIRROR MODULES PRODUCTION FLOW

The mirrors manufacturing is based on a replication process from the ultra-smooth polished master.

The mirror manufacturing process is shown in Figure 1 and is divided into the following main steps:

1. The master is created in order to have a shape that is the negative of the final reflective surface of the mirror to be produced.
2. The master is then super-polished to have appropriate roughness and shape accuracy.
3. A layer of gold is deposited onto the master.
4. The master is then mounted on a support frame that holds it during electroforming, allowing also a proper rotation inside the galvanic bath. The master is then placed in the electroforming bath containing a proprietary chemistry, where the metal layer is deposited up to the desired thickness forming directly the mirror.

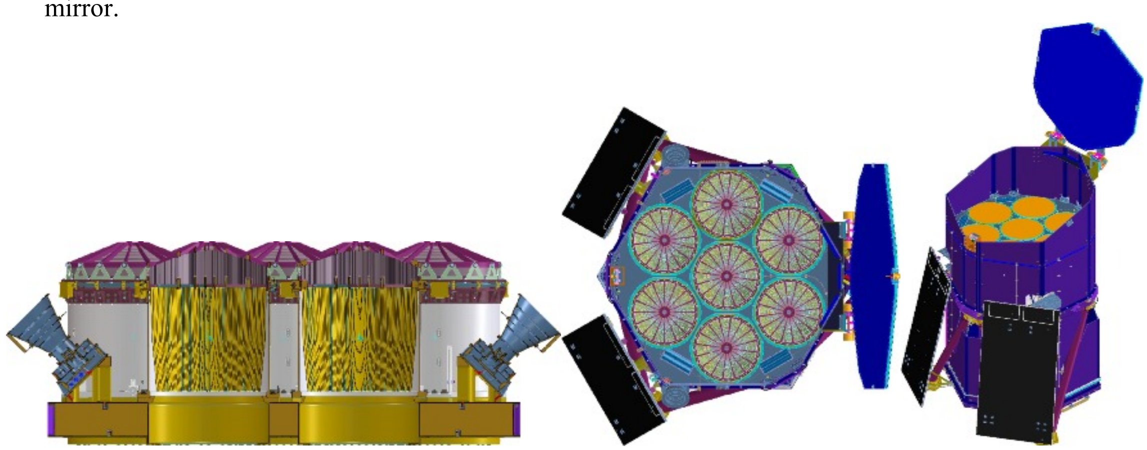

Fig. 1. eROSITA mirror modules configuration

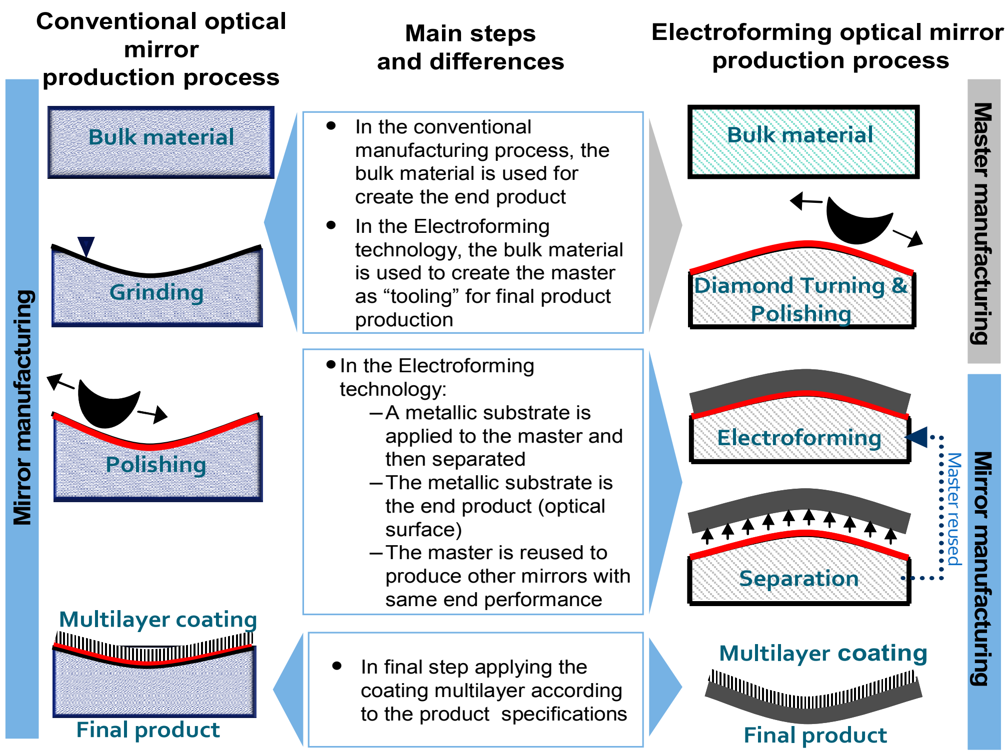

Fig. 2. Electroforming process

5. After the electroforming process is completed the mirror and the master are separated by thermal separation. The particular properties of the separation layer ensure a clean interface separation at the original master's outer surface, thus reproducing the master's optical surface quality onto the mirror.
6. Integration in VOB
7. X-ray test

III. ULTRASMOOTH AND ULTRAPRECISE MANDRELS MANUFACTURING

In the frame of the eROSITA mission Media Lario Technologies is in charge of the production of the new mandrels from n. 27 to n. 1, which are the bigger ones. The remaining mandrels from n. 54 to n. 28 are provided by the Max Planck Institute and are the ones used for the ABRIXAS mission.

The mandrels manufacturing holds a crucial role in the process of fabrication of the X-ray optics. In fact, the shape accuracy and the roughness of the mirrors replicated are strongly affected by the mandrel starting quality. For the mandrels production a new process has been derived from the one used for the manufacturing of past mission mandrels (JET-X, XMM).

Following that approach the mandrels were machined from a solid block of a special aluminum alloy and coated with a NiP alloy by means of an electroless process.

A proprietary multistep surface finishing process has been qualified enabling to reach the demanding performance requirements required by the eROSITA mission. In fact the angular resolution of the eROSITA telescope needs to be 15 arcsec HEW or better. Replicated mirrors with performance down to 12 arcsec have been obtained using mandrels that have superior accuracy (i.e. typically a factor of two or more better).

A series of eROSITA flight mandrels have been recently manufactured and tested showing the possibility to obtain very low roughness values and the needed shape accuracy<6 arcsec HEW. The production of the remaining flight quality mandrels is currently ongoing.

The metrological characterizations of the superpolished mandrel mid-scale error and micro-roughness have been performed by using different non-destructive metrological systems that allow characterizing the topography of a surface into a broad band of spatial frequencies. Concerning mandrel figure errors, the shape accuracy error has been effectively measured with LTP (Long Trace Profilometer). LTP is a slope-sensitive measuring instrument, based on the original concept of the pencil-beam interferometer of Von Bieren, used to measure the slope error of the axial profiles. The slope error accuracy at each measurement point is typically less than 0.5 arcsec, corresponding to accuracy on the profile in the order of 20 nm, over 1 meter travel range.

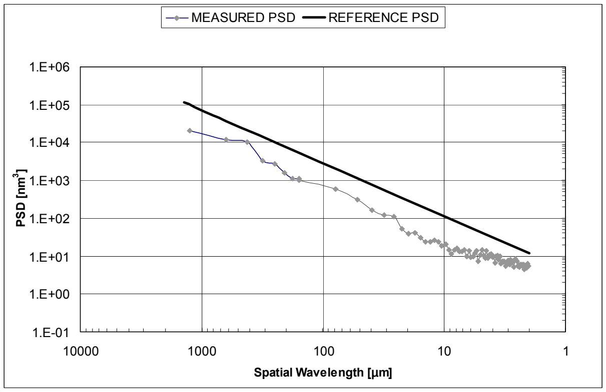

Fig. 3. One-dimensional PSDs compared with eROSITA reference PSD

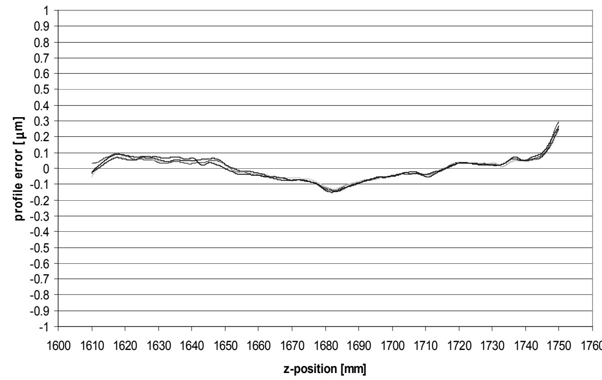

Fig. 4. Axial profiles

A new mandrel profilometer/rotondimeter allowing to take all geometrical mandrel properties (roundness, absolute diameter, etc..) and profiles with accuracy better than lambda/10 has been designed and built by MLT in order to accomplish to future mandrels production needs.

The superpolished mandrels have been measured over spatial wavelength range between 1.25mm and 0.002mm using different magnification of Phase-Shift Interferometer (PROMAP) instrument (40x and 2.5x). The resulting Power Spectral Density is reported in Fig. 3. The micro-roughness and the medium scale errors are in the order of 0.2-0.3 nm rms. The surface has been polished down to the remarkable roughness level of Sq = 0.20 nm as calculated by averaging the PSDs from 24 measurements acquired over the mandrel optical area. Also the mid-spatial error has been brought to the desired value of Sq = 0.30 nm as calculated by averaging the PSDs from 24 measurements taken over the mandrel optical area.

The axial profile error has been measured by using high accuracy LTP profilometer at 4 equally spaced azimuthal angles (i.e. each 90deg). The raw data have been Fourier filtered with a low-pass 3.5mm cut-off wavelength corresponding to the noise limit of the instrument. The axial profile error of the finished mandrel is reported in Fig. 4 showing Peak-to-Valley value of 300 nm. The axial slope error contribution to the HEW has been calculated by ray-tracing software starting from the axial profile error data with 3.5mm cut-off filter. The 50% of the encircled energy gives a HEW = 4.7 arcsec

IV. MIRROR MODULE SHELLS ELECTROFORMING

The mandrel is coated, via a proprietary process developed by MLT, with a thin layer of gold, in order to allow the separation from the mandrel and provide optical coating at the same time.

The coated master is then mounted on a support frame that holds it during electroforming, allowing also a proper rotation inside the galvanic bath. The master is then placed in the electroforming bath containing a proprietary chemistry, where the metal layer is deposited up to the desired thickness forming the structural part of the mirror.

The shells are electroformed on the mandrel in a dedicated bath able to manage up to four mandrels at the

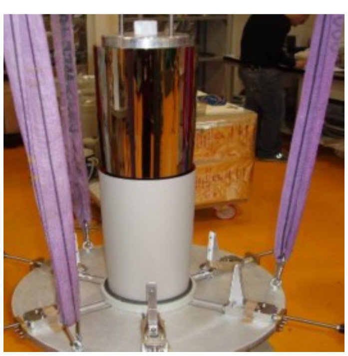

Fig. 5. Shell Release

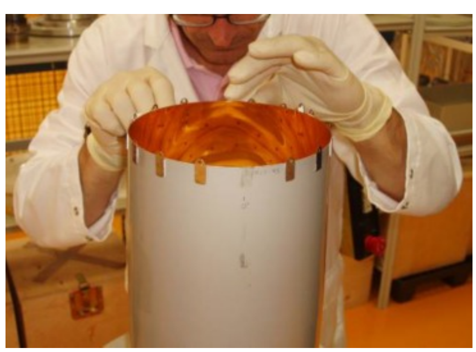

Fig. 6. Shell under preparation for integration

Fig. 7. Shell ready for integration

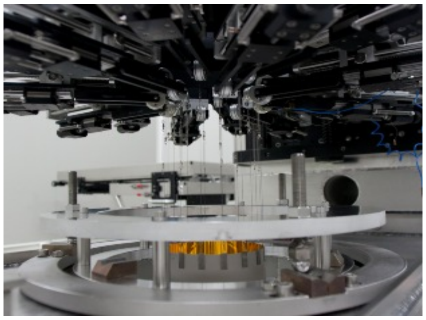

Fig. 8. Measurement of single shell performances on AVOB

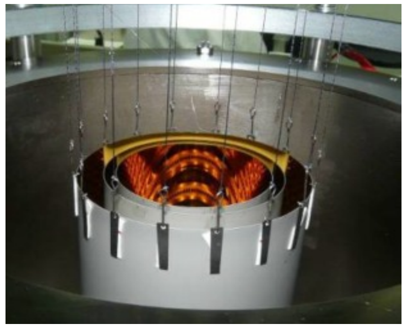

Fig. 9. Integration of Mirror Module with AVOB

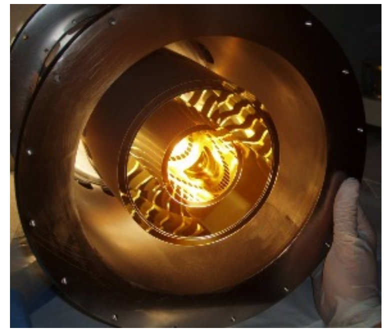

Fig. 10. Prototype Mirror Module integrated

same time. After the electroforming process is completed the mirror and the master are separated thermally, thanks to the difference between the master and shell coefficients of thermal conduction (see Fig. 5). The particular properties of the separation layer ensure a clean interface separation at the original master's outer surface, thus substantially reproducing the master's optical surface quality onto the mirror.

The shell is then inspected and prepared for the integration into the mirror module (see Fig. 6).

It has to be noticed that, with optimized thicknesses ranging between 0.2mm and 0.6mm, these shells are half of the thickness of the XMM-Newton Telescopes shells. Nonetheless mirrors with HEW of better than 12 arcsec have been produced. Moreover performances similar to XMM in terms of HEW at mirror module level have been obtained with shorter shells (eROSITA's shells are 300 mm long wrt 600 mm on XMM) and reduced focal length (7500 mm on XMM wrt to 1600 mm on eROSITA).

V. MIRROR MODULES ASSEMBLY AND INTEGRATION

In the final production step the shells are integrated into the mirror module.
The integration method is in principle the same as for XMM, but with the difference that the mirror support structure is already fully assembled prior to shell integration. Corresponding to the need of highest quality mirror modules and shells, the integration process is optimized involving specific solutions including:

- Suspending the shells in most stress free condition using 16 supports (see Fig. 8 and Fig. 9).
- While a mirror shell is suspended, optical metrology based on full illumination is used.
- Under continuous metrology the mirror shell is glued into the grooves of the spider wheel using a bespoke Advanced Vertical Optical Bench (AVOB) the shells are precisely lowered into the spider that holds all the shells together (see Fig. 11 to Fig. 13, courtesy of the Max-Planck-Institut für Extraterrestrische Physik).
- The stress free condition is maintained until the glue is cured sufficiently to allow removal of the suspension.
- The shells are integrated one by one starting with the innermost shell.

The quality of the integration process was verified, using dummy structures as depicted below. These structures were used to verify that the shells were not distorted, e.g. by non-uniform suspension or shrinkage of the glue, and that the shells are well co-aligned.

Fig. 11. eROSITA Flight Model spider

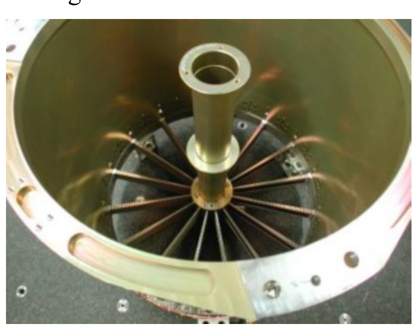

Fig. 12. Blocking shell and Mirror Interface Structure mounted on spider

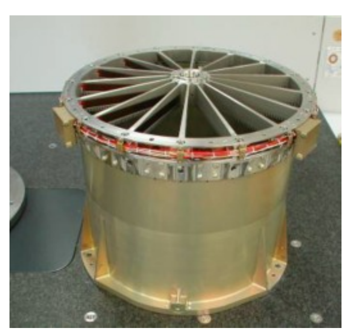

Fig. 13. Mirror module ready for shells integration

VI. X-RAY TEST

Although the metrology by various optical means is very useful for performance, analysis and screening illumination with X-rays is finally necessary to demonstrate and characterize the imaging capabilities of X-ray optics. These X-ray tests are performed in vacuum chambers with an X-ray source in great distances from the optics to be tested in order to illuminate with an almost parallel beam.

The eROSITA mirrors and mirror modules are being tested in the test facility PANTER of the Max-Planck-Institut für Extraterrestrische Physik (MPE). Its vacuum chamber has been used in the past for the verification of the X-ray performance of complete instruments like the ROSAT or XMM telescopes (see **Fig. 14**). The position of the X-ray source is at the end of a 120 m long tube attached to the chamber.

The best mirrors so far produced in the eROSITA project were integrated in a cylindrical mechanical structure (see Fig. 13). This test mirror module contained five mirror shells with diameters between 76 mm and 178 mm. The four smaller shells (54, 49, 29, 28) were replicated from ABRIXAS mandrels manufactured and refurbished by Zeiss (28 refurbished again by MLT), and the largest shell (25) from a mandrel newly produced by Media Lario Technologies. The focal images of each mirror shell and of the complete module were taken at different photon energies in order to account for the effect of energy-dependent scattering fractions.

The camera used for these images is a pnCCD detector being a precursor of the cameras which are developed for the eROSITA telescope. With the focal length of 1600 mm their pixel size corresponds to an angular resolution of 10.7 arc seconds. This is not subtracted for the numbers reported in **Tab. 1**; however, MPE made use of the effect of "split events" in the detector which allows sub-pixel resolution in the order of 4-5 arc seconds.

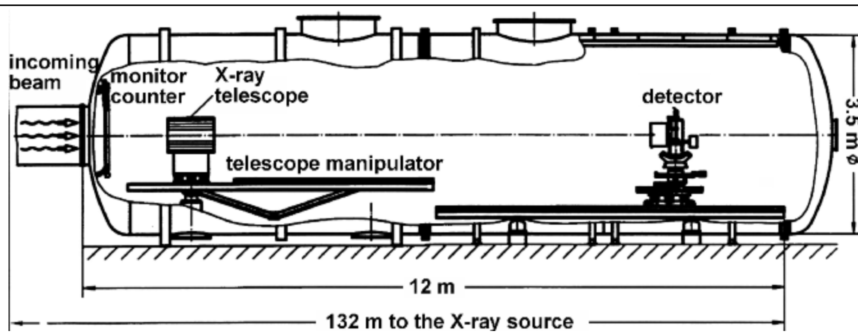

Fig. 14. Schematic view of the vacuum chamber of MPE's PANTER X-ray test facility

Tab. 1. Summarized X-ray performance - expressed by HEW and W90 - of the Test Mirror Module; *with sub-pixel resolution of the camera

Mirror shell	0.28 keV	1.49 keV	5.41 keV	8.04 keV
54r01 Ø 76.3 mm	16.1" HEW 61" W90	15.7"/12.6"* HEW 51" W90	16.5" HEW 82" W90	16.5" HEW 88" W90
49r05 Ø 88.6 mm	17.4" HEW 100" W90	17.2"/13.6"* HEW 95" W90	18.0" HEW 160" W90	18.0" HEW 212" W90
29r02 Ø 158.3 mm	20.5" HEW 113" W90	19.6"/16.7"* HEW 116" W90	21.6" HEW 163" W90	
28A2r01 Ø 162.9 mm	17.7" HEW 70" W90	18.0"/15.2"* HEW 72" W90	19.5" HEW 149" W90	
25A3r01 Ø 177.7 mm	15.6" HEW 63" W90	15.6"/12.1"* HEW 56" W90	16.6" HEW 95" W90	
Complete module		18.3"/15.3"* HEW 89" W90		17.6" HEW90 157" W90

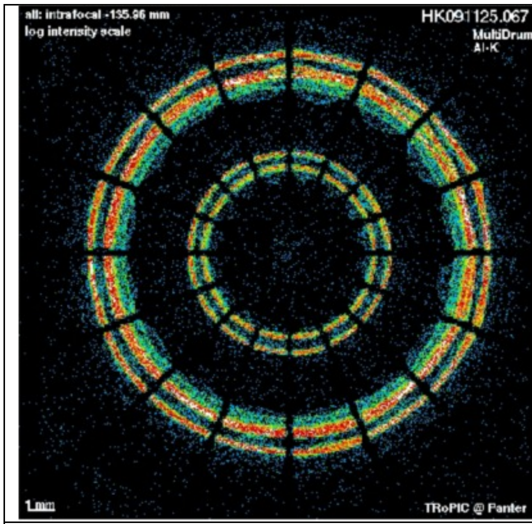

Fig. 15. Intra-focus image of the Test MM at 1.5keV

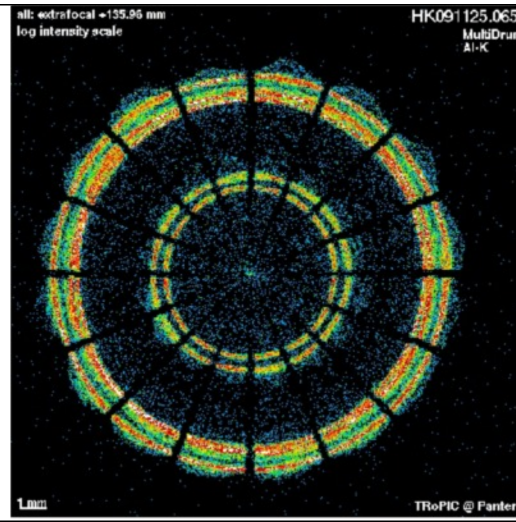

Fig. 16. Extra-focus image of the prototype at 1.5keV

The image of the complete module is not only the result of the performance of the single shells but also dependent of an accurate alignment of all mirror shells. Here, all five foci are located within a circle of 64 µm which is less than one detector pixel. The depth of the focus is within ±0.44 mm.

Beside the focal images intra and extra focal images were taken for diagnostic purpose (see **Fig. 15** and **Fig. 16**). These images show azimuth resolved error contributions which can be partly assigned to roundness errors, distortion and effects of integration. It must be noted, however, that it is in general not possible to assign certain features of the X-ray images to certain locations on the mirror shell, in particular in length direction.

The x-ray test is the final verification of the mirror and telescope performance. Additional metrology steps are used for more detailed evaluation of the error sources, mainly constitutet by profile errors. Such profile errors are caused by replication from the mandrel, eventually with magnification, and by internal stress. In the frame of the development activities the processes are optimised as needed to reach the required telescope performance. To reach good x-ray performance, thorough execution of the validated processes for manufacturing and integration is obligatory. Even small deviations can cause significant non-recoverable performance errors. This is most important, since seven high quality mirror modules with 54 mirror shells each are needed. This is an even higher challenge tahn the production of the XMM mirror modules, which MLT has successfully performed more than 10 years ago.

VII. CONCLUSIONS

The eROSITA mission is very challenging in terms of performances requested and volume of production, however the consolidated experience of Media Lario Technologies enabled the development and qualification of the entire production flow from the mandrels design to the Mirror Modules integration, achieving the required optical performances.

Moreover the core competencies in the electroforming field acquired by MLT will permit the production and integration of one shell per day, a pace unachievable by any other mirror production technology.

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