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Ion beam figuring technique used as final step in the manufacturing of the optics for the E-ELT

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Abstract. The INAF-Astronomical Observatory of Brera (INAF-OAB) is exploring the technical problems related to the ion beam figuring (IBF) of the Zerodur hexagonal mirrors (1.45 m corner to corner) of M1 for the European Extremely Large Telescope (E-ELT). As starting step a scaled down version mirror of the same material having size of 1 m corner to corner has been used to assess the relevant figuring problems. This specific mirror is spherical and has a radius of curvature of 3 m which allows a simple interferometric measurement setup. A mechanical support was designed to minimize its deformations due to gravity. The Ion Beam Figuring Facility used for this study has been recently completed in the Brera Observatory and has a figuring area of 170 cm x 140 cm. Aim of this study is the estimation and optimization of the time requested for the correction of the surface using also strategies to control the well-known thermal problems related to the Zerodur material. In this paper we report the results obtained figuring the 1 m corner-to-corner test segment.

Key words. Ion Beam Figuring – Removal Function – Hexagonal Mirror Segment – Zerodur – E-ELT

1. Introduction

The E-ELT will be operative around 2024 and at that time it will be the largest telescope in the world. Its main mirror (M1) will have a diameter of 39.3 meter and a collecting area around 15 times larger than the best instruments nowadays available. This is truly a technically challenging instrument, optically and mechanically. It will have native built-in adaptive optics so to be very nearly diffraction-limited over the entire field of view of around ten-arcminute. The segmented main mirror M1 will be assembled by 798 hexagonal segments, each 1.45 meters corner-to-corner wide, 50 mm thick. M1 will be a f/0.88 elliptical mirror with a radius of curvature of 69 m and an 11-meter central obstruction. The aspherical mirror is divided in six sectors of 133 segments, each one different in optical prescription. Each sector is identical to the others. The reflective coating of the segments will need a replacement every 18 months (one or two segments replaced every day) so that a total of seven sectors will be procured (six plus a spare sector). This will permit to have an immediate segment replacement. For this reason the total number of segments will be of 931 pieces. The hexagonal segments will be manufactured in a glass ceramic material, probably Zerodur. The segments will be placed and bonded on active optic supports able to tune finely their shape so to correct the residual shape errors (e-elt constr. prop. 2011). These two components, segment and segment support, will be integrated once and for all together forming the segment assembly that will be installed on the telescope main structure. The manufacturing chain of the segments foresees that after the mechanical lapping (Gray C. et al. 2013), and having reached a suitable accuracy in shape, the final figuring passage will be done with IBF to bring down the surface remaining errors to the final specs required (goal of 20 nm rms after IBF and 5 nm rms after active correction with the segment support). In this phase, the segment will have its own remaining errors plus the print-through and distortions introduced by the support itself. All these errors will be corrected by IBF with the segment assembly under vacuum.

2. Ion beam figuring

The IBF is a technique that employs an ion beam to remove in a very controlled way atomic layers of material from an optical surface so to correct the shape errors. INAF-OAB has built an R&D IBF facility (Fig.1) having a working area of 1.7 m x 1.4 m (Ghigo M. et al. 2014). Since the mechanical frame is vertical, the movement of the ion source is in a vertical plane and also the optics to be corrected needs to be mounted vertically. The movement of the source is done in three axis, xy on the vertical area and z horizontally, to keep the distance optic-to-grids at a constant value in the case of curved optics. The maximum z sag extension is 60 mm. The ion source has two graphite grid sets having different sizes: a 50 mm collimated grid set and a 15 mm focused grid set. The first used for corrections of long spatial wavelengths, the general shape of the mirror, the second for the retouch of smaller errors, for example print through. The power of the beam can be regulated from 6 to 240 watts depending on the removal rate requested for the specific job.

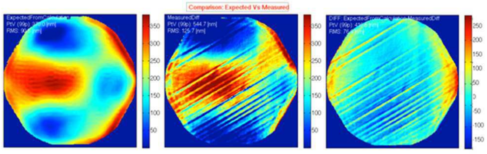
2.1. Hexagonal mirror correction

Under a cooperation agreement, Glyndwr University, N. Wales, has provided to INAF-OAB an hexagonal Zerodur mirror 1 m corner to corner for initial tests related to the IBF process. This mirror is spherical with a RoC of 3 m (sag of 41 mm) so to permit its easy interferometric measure in house. Previously it was used for polishing and figuring tests on a Zeeko machine, resulting in a textured surface not representative of a true segment but useful for preliminary IBF tests. We measured the starting surface of the Zerodur hexagonal mirror and we found it affected by a relevant amount of surface error respect to a sphere, of about 3500 nm PV and 600 nm RMS. This large error was reduced removing mathematically the low order components so to obtain an initial surface of about 100 nm RMS that was considered the starting surface for IBF. An important issue to be considered is the heating of the surface when hit by the IBF beam during the figuring. It is known that the Zerodur is affected by thermal hysteresis for temperatures above 120-130 C. If not taken in consideration, the ion figuring of a Zerodur optic may therefore result in distortions induced on the optical figure of the surface. Different solutions have been proposed to solve or mitigate this issue, like reducing the ion beam power or increasing the scanning speed passing more than once on the same points of the surface. Another possibility is to modify the raster scan movement

Fig. 1. INAF-OAB IBF Facility

using a so called boustrophedonic scan pattern (ion beam figuring 2010) where, during the raster scan process, the ion head is translated between columns (or rows) of more than 3 sigma of the removal function size so to avoid to add heat to points recently already heated. To study the thermal issue on the Zerodur a number of thermal probes were attached on the back of the mirror. The data were used to infer the temperature on the mirror front surface.

We used a setup for the IBF so to obtain a beam power of 75 W. With this a total figuring time was computed of 17 hours. We used this setting as an intermediate power with the goal to remove or, at least, mitigate the thermal issue. The surface error map we chose as the input for the figuring correction was the one in Fig.2 (left) having 100 nm rms error. The measured material removed is shown in Fig.2 (center) and it resembles to the input, roughly. Their difference gives the residual map in Fig.2 (right). Some distortion of the optical figure was still present, which accounted for about 75 nm RMS. The estimation of the max temperature achieved on the front surface during this figuring run was of 160 C near the left edge due to a combination of relatively long figuring times and reentering of the source in a contiguous column just figured. In general the temperature was oscillating around 130-140 C. Apparently these values of temperature on the surface were able to produce some permanent figure deformations.



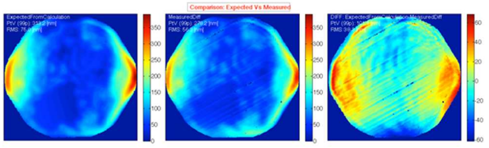
Theoretical material to be removed

Measured material removed

Difference

Fig. 2. Result first IBF run

The next test was made after a modification of the movement control software. This software modification permitted to half the additional time required for the figuring, merely associated to the finite-speed motion of the scanning axes. With the new software implementation we were hence able to reduce sensibly the figuring time (and hence the heating) without changing the power of the beam, keeping it at the same power of 75 W and with a 7 hours figuring time. The results are displayed in Fig.3. The input data (Fig.3 left) we chose for the ion figuring was the surface error left behind by the previous iteration, the one shown in Fig.2 (right) with the high frequency traces removed (that we filtered out before any computation).



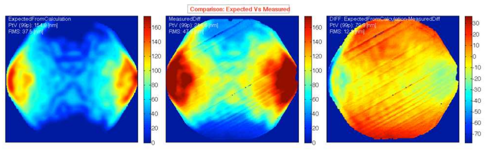
Theoretical material to be removed

Measured material removed

Difference

Fig. 3. Result second IBF run

After the figuring the material removed was that shown in Fig.3 (center). The agreement with the input map is reasonably good. The difference residual map is shown in Fig.3 (right) and is limited to 40 nm RMS. After removal of the low frequency terms according to E-ELT specs, we obtained a residual error map having an RMS of 10 nm, not yet within the requirement specification (goal of 5 nm surface RMS) assumed for the mean primary E-ELT segment. We performed the last figuring iteration at a very low ion source power level, 12.5 W. The results are shown in Fig.4 (right). A final residual error of 13 nm RMS was obtained. This value is well below the 20 nm rms required for the mean segment. A fig-



Theoretical material to be removed

Measured material removed

Difference

Fig. 4. Result third IBF run

uring time of 19 hours was computed for the correction. Again, the input data was the residual error map from the previous iteration and at this low power level we expected no thermal problems. After removal of the low frequency terms according to E-ELT specs the residual map of Fig.5 was obtained. Finally, the RMS value of the residual error was equal to 4 nm, which is below the goal specification (5 nm surface RMS) assumed for the mean primary E-ELT segment. Also, the highest temperature obtained on the optical surface was of 68.7 C, very low. As shown in Fig.6, the total figuring time needed to correct the mirror was of 43 hours (run1=17 hr + run2=7 hr + run3=19 hr). We expect this cumulative time to be not representative of the true figuring runs required for the correction of a real segment, this total time being also influenced by the issues to understand the thermal problem. A better time estimation will come from the future activities regarding the correction of a real scale 1.45 m hexagonal segment without high frequencies texture and initial errors in line with what prescribed after lapping (100-200 nm rms).

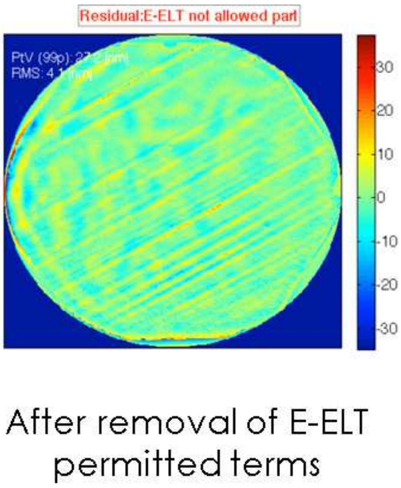


Fig. 5. Residual error after active correction (4 nm rms)

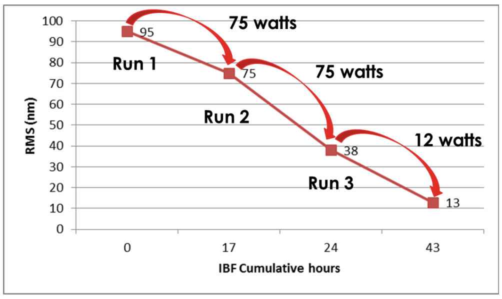


Fig. 6. Summary of IBF runs

3. Conclusions

The present study is in its early stage but already a large quantity of information has been gained in particular on the thermal issue. Our IBF facility has shown the capability to figure large optics with success, correcting the chosen initial error of 100 nm RMS down to 4 nm RMS in specs with the E-ELT requirements. It will be important to start a new phase using a full-scale segment so to find a better evaluation of its tipical IBF figuring time. The use of a removal function having intermediate power between 75 and 12.5 W will help us to manage the thermal issues of the Zerodur having also an acceptable removal rate.

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