The E-ELT M4, on its way to becoming a reality

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ABSTRACT

The final design of the M4 Unit is almost complete. Most of the critical prototypes have been successfully tested and a few are currently under test. The first subsystems are already in manufacturing phase. A detailed description of the design characteristics is provided in this article. A comparison between performance analysis and prototype results is provided for the critical items. The next steps are also described including the detailed test plan of the segment prototype setup.

1. INTRODUCTION

The final design review will take place in December 2017 concluding a series of design reviews for all subsystems and two years of design and analyses [1]. In the last months, several tests have allowed validating critical items evidenced at the preliminary design review. We report hereafter the design of each subsystem, providing detailed characteristics of the main elements and indicating expected performance. We then focus on the validation of the critical items. We conclude with a description of the next steps.

2. DESIGN DESCRIPTION

M4 Mirror and its cell

The M4 mirror (Figure 1) is an evolution of the adaptive secondary mirror technology developed for MMT, LBT, VLT and Magellan.

The concept has not changed: a thin mirror populated with magnets is levitating 100 microns away from electromagnetic actuators fixed on a reference structure. With respect to all previous systems, the following changes have been implemented:

- The mirror shell is segmented in six petals
- The mirror lateral membranes are mounted on the external part of the shell petals
- The reference structure is now a silicon carbide body on which small hexagonal borosilicate tails are glued to make the capacitive sensors armatures. The silicon carbide reference body is made of six segments brazed together
- The capacitive sensor armature and its signal pick-up method have a new design
- The actuators are grouped on printed circuit boards referred to as ‘bricks’ which include the power supply board, control board, voice coil driver board, cap-sense board and a coldplate using gas cooling

- Actuators bricks are directly mounted on the Reference Body, which thus makes also the function of the structural support of the deformable mirror assembly
- This reference structure is handled by its cell with axial lateral supports. The cell is also used to fix the hexapod interface.
- The system is cooled by gas. This was recognized as a good way to drastically reduce the risk of problems arising due to leakage of liquid coolant. The gas cooling system has been prototyped and extensively simulated, optimized and tested as reported in [2].

Figure 1: M4 mirror and its cell final design

Reference structure:

The choice of silicon carbide has been done after a detailed trade-off analysis during the preliminary design phase. The reference structure needs to be stiff enough to provide a good reference whilst at the same time having the following characteristics: not too heavy, not deforming too much with temperature variation and not too fragile. CFRP , aluminum and zerodur have also been considered but both CFRP and aluminum did not fulfil stability requirements while Zerodur was considered more risky in terms of manufacturing than silicon carbide. The structure is made of six identical segments brazed together. The front face is then polished to reach the flatness requirement needed for the mirror.

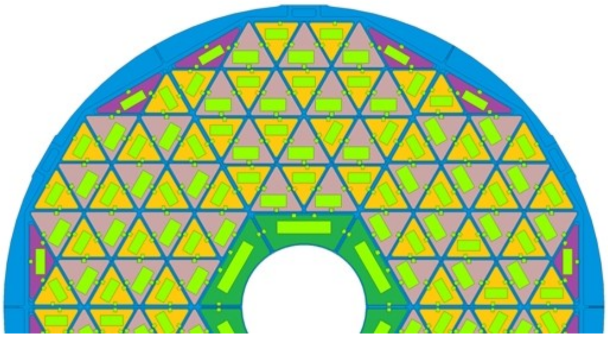


Figure 2: Back face of the reference structure showing the cell geometry.

The back face of reference structure is composed of 174 cells holding the 174 bricks of the system as shown in Figure 2. As the shrinkage of the silicon carbide cannot determined in advance, the design has been optimized to accept this uncertainty. This optimization is done both at the level of the cells by planning for a spacer whose thickness will be adapted when mounting the brick fixation interface and by designing actuator holes slightly larger than required.

The oversized dimension of the actuator holes is corrected by gluing borosilicate tiles on the front surface of the reference structure. The objective of these tiles is to provide a reference surface with the proper resistance for the capacitive sensor armature as well as to provide a surface to mount the capacitive sensor connector at the proper place.

Capacitive sensors:

Figure 3 shows the solution adopted: the pin comb on the upper side of the connector relies on a coated and chamfered surface around the actuator hole (capacitive sensor armature). The leaf spring geometry in the middle region provides pre-tension force against the three snap-in legs on the bottom side of the reference body (not visible in Figure 3). The sphere (shown is only one of two) is a permanent magnet and ensures an electrical contact with the counterpart mounted on the printed circuit board. The counterpart for the magnetic contact is a spring cage, whose main role is to decouple the contact force between the armature connector and the printed circuit board. The key aspects of the described connector design are twofold:

- the pin comb provides high reliability of the contact between the capacitive sensor armature and the armature connector itself;
- the magnetic contact realized through the magnetic ball and the spring cage guarantees a highly reliable contact thanks to the high magnetic force. The magnetic force is high because it is a pure internal action, which in principle does not involve any direct system deformation. The entanglement between the board and the reference body is driven by the stiffness of the spring cage, which is linear and sufficiently soft in the range of relative motions foreseen by design between the board and the reference body itself. In particular, no hysteresis is introduced.

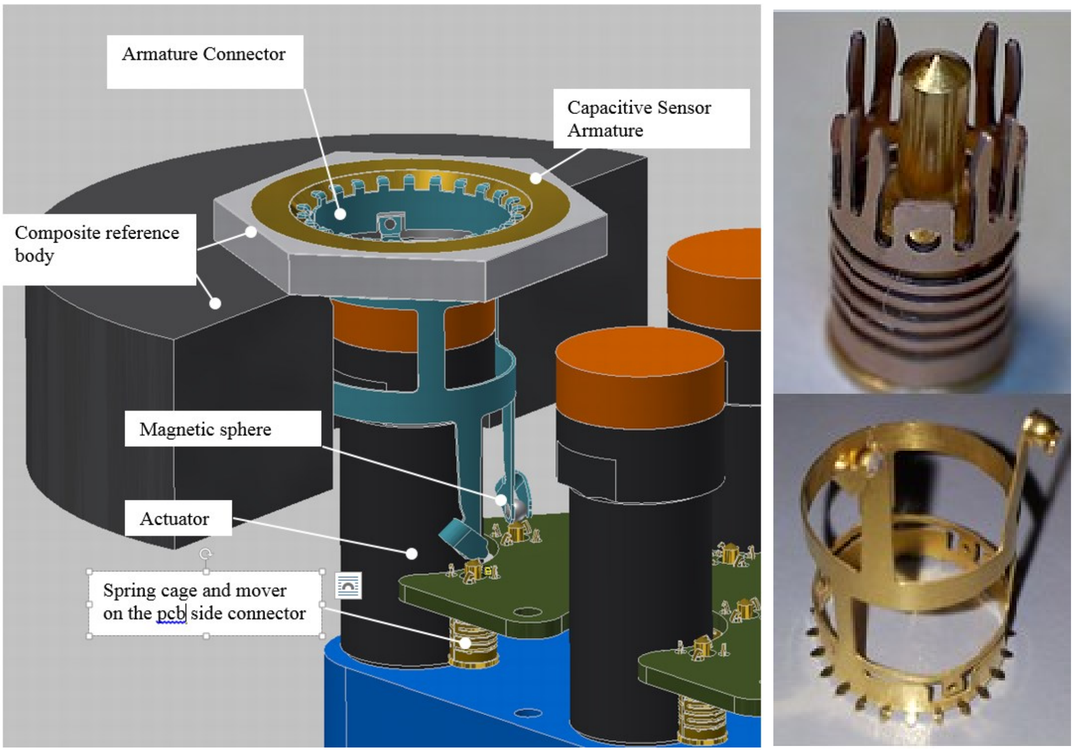


Figure 3. Sectional view of the capacitive sensor armature connector concept (left), detail of the spring cage connector mounted on the electronic board (top-right), detail of the armature connector (bottom-right).

Bricks

As the M4 mirror need more than 5000 actuators, the possibility to dismount actuators without dismounting the mirror was considered mandatory since the early development phases. Four types of bricks are needed to populate the M4 reference structure. The bricks incorporate the actuators, the brick power supply board, control board, voice coil driver board, cap-sense board and the spring cages associated to each capacitive sensor connector.

The brick power supply board provides the power to the voice coil motors, capacitive sensor board and to the control board. It also collects the diagnostics data of the brick including temperatures, power monitor and accelerometer.

A Field Programmable Gate Array (FPGA) is the main component of the digital part of the control board, managing the high-speed link, receiving the mirror commands and passing them to the actuator control loop and executing the actuator control loop in parallel for all actuators of the brick. The FPGA is also acquiring data in parallel from the ADCs from each capacitive sensor as well as updating in parallel all the DACs to drive the coil currents. Finally, the FPGA is responsible for some part of the housekeeping of the brick and it manages the real-time data acquisition by storing it to the local SDRAM and sending it to the external supervisor.

Brick type	Brick quantity	Actuators quantity
A	72	36
B	84	28
C	12	28
D/E	6	69
Total	174	5694

Table 1: actuator number for each brick configuration

The brick control board and the brick power supply are mounted on the opposite faces of the aluminum heat sink. This subassembly unit is identical for all bricks. This allows an extremely compact design, essential for the M4 mirror.

The performance analysis of the system has been extensively studied during the final design phase as reported in [1] and [6]. A multiphysics analysis of the system has been developed and it has been also used to study the earthquakes load cases as explainer in [5].

The M4 Mirror shells

Due to the size of the mirror, it was considered too risky to manufacture and integrate a monolithic shell. The design with 6 segments was presented at preliminary design review and the final design has not changed this number of shells. The membranes have been redesigned to improve the lateral restraint of the shell. Each shell is restrained laterally by 25 pairs of membranes sandwiching the mirror outer diameter. As on all adaptive secondary mirrors, the common reference signal needed for the capacitive sensors should be injected on the thin shell back side coating layer. Each shell is integrated with permanent magnets glued on the back side of the shell.

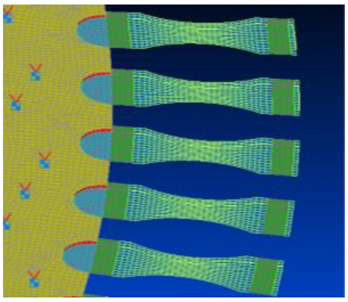


Figure 4: design of the membrane restraining laterally the mirror shell

Hexapod

The hexapod design and layout has been optimized during the final design phase to allow an easy access to the M4 DECam and DESI hexapods, a few aspects have been modified: instead of using the power brick for the CPU and driver and having filters, the new design is using a compact 'intelligent' driver and a separated CPU linked by Ethercat connection. This allows a compact and lighter design, reducing the number of cables and connectors. This new design will have a faster response, a lower heat generation and it will be easier to maintain.

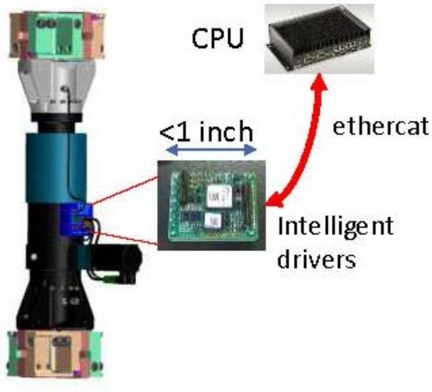


Figure 5: Hexapod leg design

M4 cell, M4 mounting structure and rotator

The M4 cell has been designed to support the reference structure as a mirror. It is using axial and radial support, fulfilling the stringent stability requirements needed for gravity orientation change and severe environmental conditions. The M4 reference structure is interfaced to its cell by several structural bondings. The cell also provides a safety restrainer to avoid any pieces falling in case of bonding failure. The bonding is considered critical and a validation campaign has been done before the final design review.

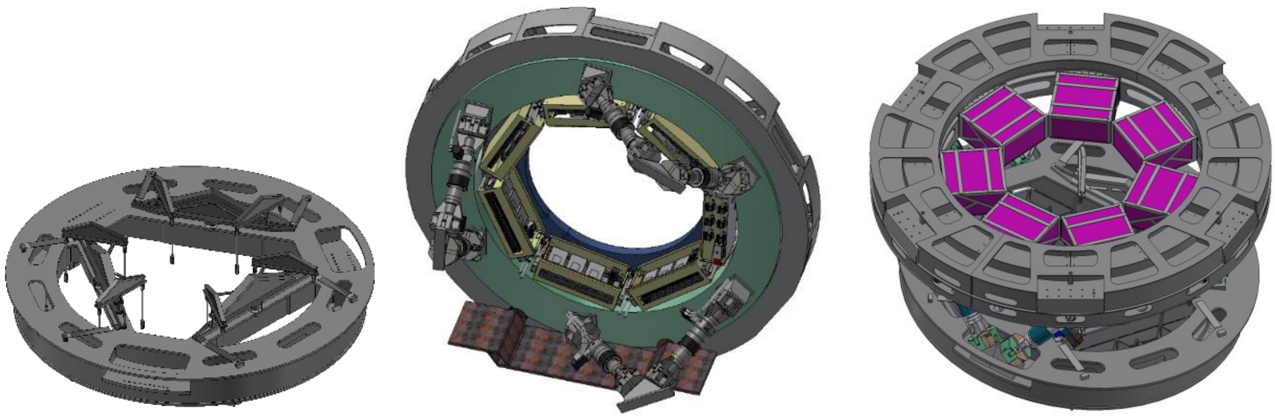


Figure 6: Left: M4 cell holding the reference structure with axial and lateral supports. Center: mounting structure holding the hexapod, the Nasmyth rotator as well as the electronics crates. Right M4 unit seen from above with the electronics crates.

Table 2: M4 unit mass breakdown

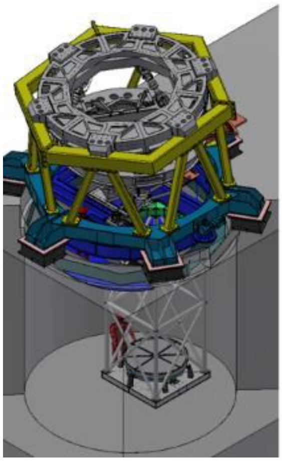
M4 sub-assembly	**Weight (kg)**
Kinematic support	7581
Mass attached to M4 KS	512
Mirror mass attached to RB Cell	2462
Total	10555

The mounting structure has been optimized in weight to fulfil the 10 ton requirement. It includes a permanent platform for maintenance purposes. The structure is holding the cable wrap and the cabinets. The cable wrap has two operational positions and few additional ones for maintenance of the bricks. The position of the electronics cabinets has also been optimized for accessibility.
The mass breakdown is provided in Table 2.

M4 optical test tower

An optical test tower is requiredfor the optical calibration of the mirror. The M4 mirror will be tested facing down, at normal incidence, with visible interferometry. The strategy for optical calibration is discussed in [3], [7] while the design is presented in [4]. The Optical Test Tower (OTT) shall allow the flattening and co-phasing of the M4U shells and shall provide an absolute measurement of its shape (excluded global tilt and global piston). To cover all the M4U surface the optical beam is moved below the unit in radial direction (-50mm to 400mm from the M4U OV) thanks to the sliding tower and in azimuthal direction (360°) thanks to the rotating ring. The sliding tower allows also measurement of the inner part of the M4M ,verifying that all the six shells are co-phased.

Two optical configurations are implemented on the OTT. In the Large Aperture Interferometric mode (LAI) the entire M4U segment is imaged and controlled; the Sub-Aperture interferometric mode (SAI) is instead based on a 100 mm test beam to provide the high spatial frequency verification of the M4U. Such separated test solution is requested to improve the measurement resolution and accuracy.



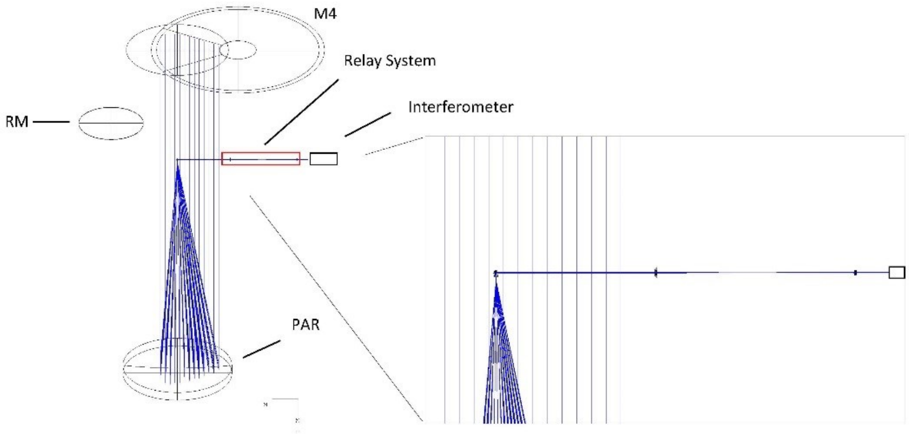


Figure 7: Optical test tower opto-mechanical design (left) – Optical design (right)

To limit the beam diameter while avoiding sub-aperture stitching, a macro-stitching approach is foreseen for the calibration and testing of the M4U. Accordingly, the LAI mode is designed to cover the single shell, allowing the separate measurement and calibration of the mirror segments (segment view) and the subsequent recombination of the phase maps to obtain the entire mirror shape.

A global measurement of the M4U, although partial, is obtained by positioning the testing beam at the center of M4U (center view) with the goal of sampling the differential piston and tilt of the shells.

The quality of the M4U at the small spatial scales of the inter-actuator distance shall be certified with a second measurement setup, consisting of an interferometer with a collimated beam of 100 mm in diameter. To image different regions on the M4U, the setup is mounted on the Sliding Tower (STO) and rotates with the truss under the M4U to image the whole mirror.

CRITICAL ITEMS VALIDATION

During the final design phase, a large amount of time has been dedicated to the validation of the critical items: manufacturing of the silicon carbide reference body, manufacturing and testing of a hexapod leg, manufacturing of the first two types of bricks, associated electronics, control aspects and structural bonding aspects. In parallel, the manufacturing of the M4 mirror shell has also started to ensure delivery on time.

Silicon Carbide validation prototype and first segment manufacturing

The silicon carbide reference structure has been identified as a critical item during the preliminary design phase due to its high rigidity to weight ratio and due to the stringent requirements for the positioning of the holes and ribs. Mersen Boostec proposed to validate the process through various prototypes. The objective was to validate the actuator hole position (depending mainly on the shrinkage of the piece), flatness of the front face as well as thickness, positioning and perpendicularity of the ribs.

A reduced scale prototype was successfully manufactured after some trials at the end of 2016. Mersen Boostec started the manufacturing of the first M4 segment in March 2017. The first segment had some deformation of the front face, somebad shrinkage (inducing a wrong position of some holes) and two external ribs bent. A second segment has been manufactured: the shrinkage problem has been solved as well as the front face deformation but the two external ribs are again bent by some millimeters preventing mounting of the corresponding bricks.

Figure 8: second segment manufactured. The most left and right ribs are bent by 2 millimeters.

Mersen Boostec has defined some recovery actions for this second segment. They have also proposed some changes in the manufacturing process for the next segment. The main risk for this aspect is now the schedule risk: the reference structure is on the critical path of the M4U and several months are needed to recover the segment. Applying this recovery time to all segments could induce a late delivery of the reference structure.

Structural bonding validation

Both positioning and structural bonding are used in the M4 unit.

The positioning bonding is used for the gluing of several components: borosilicate tiles, pucks, permanent magnets, bricks restraining systems as well as M4 shell membranes are glued. Testing of the tiles bonding has been successfully validated while the bonding of the magnets and membrane is foreseen now.

The structural bonding is used for interfacing the M4 Cell with the M4 reference structure. The lateral and axial supports are bonded to the reference structure. Two different types of glue have been tested on samples. The ageing procedure and bonding procedure are still under investigation in order to determine the optimum procedures for these processes.

Hexapod Prototype

The hexapod is a critical sub-system for the M4 unit as it need to provide decentering and tip-tilt functionality to the system. The performance of the system at the level of the leg was defined as part of the requirements to be verified before the final design review. In the first phase five prototype joints have been put under load for accelerated lifetime tests. These tests demonstrated that the joints could withstand the entire lifetime of the system.

The prototype leg validation includes as well stiffness tests of the leg to characterize the actuator's stiffness, hysteresis and backlash. The testing of the actuator leg is foreseen in the next weeks.

Full segment setup prototype

A prototype equivalent to a M4 segment has been foreseen to consolidate the design before the final design review. It facilitates testing of the final actuators, 2 of the 5bricks types and the final mounting mechanism and allows testing of the electronics of the bricks as well as the capacitive sensors on a large quantity of actuators. It will provide performance consolidation on one full segment of:

- real-time and CAN interfaces,
- noise performance and assessment of dedicated grounding solutions
- new distributed reference signal concept performance+ assessment of capacitive load driving capability of the reference signal generator
- Behavior of gas cooling on a 'real' segment, also with elevation changes
- Suitability for extended temperature tests

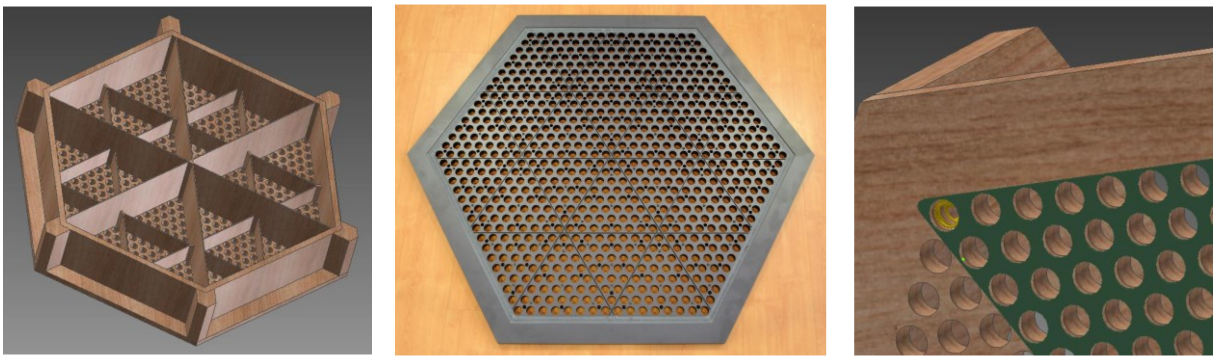


Figure 9: Full segment setup prototypemade of a nonconductive structure, identical to the final silicon carbide reference structure. It includes 10 bricks of type A and 14 bricks of type B for a total of 712 actuators. It will be used with the demonstration prototype developed during preliminary design phase which has 220 actuators.

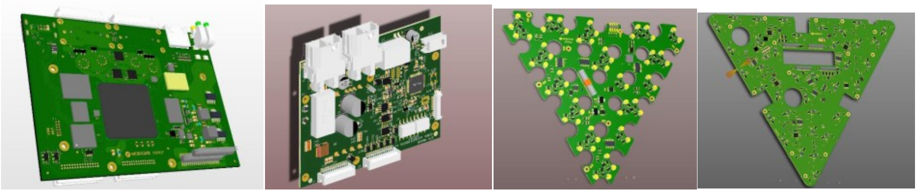


Figure 10: electronics boards for the bricks: from left to right: control board, power board, driver board and capacitive sensor board.

Mirror shell manufacturing

After a design phase and facilitation phase in 2016, the 12 blanks were produced by Schott in early 2017 and the manufacturing of the M4 mirror shell has already been started a few months. The first shell has been in the polishing phase for one month while the second is in the thickness reduction phase. The objective of REOSC is to finish the 12th shell before the end of 2020.

The mirrors are cut to the final shape once they have the final thickness requirement fulfilled. This allows REOSC to select the optimum part of the shell with respect to optical surface flatness andthickness uniformity and to avoid at the same time, wherever possible, imperfections such as bubble, inclusions, scratches.

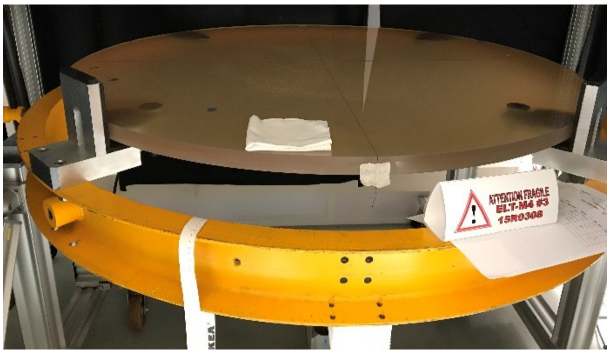


Figure 11: Shells under manufacturing: on the left during measurement inspection of the optical face. On the right at the start of the polishing of the back surface. The shell has already a thickness of 2 mm.

3. CONCLUSIONS

A detailed status of the M4 unit has been presented in the previous sections. The design is now fully consolidated. The critical items validations are current finalized. The detailed design review of each subsystem will take place in fall 2017 and the final design review in December 2017.

The manufacturing of the unit will start early 2018, the objective being to have an acceptance in Europe by mid-2023. Bythe middle of 2018the first shell will be integrated with coating and magnets.

REFERENCES

[1] Biasi, R., Manetti, M., Andrighettoni, M., Angerer, G., Pescoller, D., Patauner, C., Gallieni, D., Tintori, M., Mantegazza, M., Fumi, P., Lazzarini, P., Briguglio, R., Xompero, M., Pariani, G., Riccardi, A., Vernet, E., Pettazzi, L., Lilley, P., Cayrel, M., "E-ELT M4 Unit final design and construction: a progress report", SPIE Volume 9909, id. 99097Y 16 pp. (2016).

[2] R. Biasi, 'Direct expansion gas cooling technology applied to the E-ELT M4 adaptive mirror' [P2009], AO4ELT5

[3] M. Xompero et al, Optical calibration of the ELT adaptive mirror M4: strategy for optical measurement error estimation, AO4ELT5 (P2011)

[4] Pariani, G., 'Optical calibration of the E-ELT adaptive mirror M4: design, alignment and verification of the interferometric test tower', [P2012], AO4ELT5

[5] 'Multiphysiscs dynamic simulation of the E-ELT M4 adaptive mirror during earthquake', [P2008], Manetti, M.

[6] Biasi, R., Gallieni, D., Briguglio, R., Vernet, E., Andrighettoni, M., Angerer, G., Pescoller, D., Manetti, M., Tintori, M., Mantegazza, M., Lazzarini, P., Fumi, P., Anaclerio, V., Xompero, M., Pariani, G., Riccardi, A.,

Cayrel, M., Dierickx, P., Hubin, N., Kornweibel, N., Pettazzi, L., “E-ELT M4 Unit updated design and prototype results”, AO4ELT, October (2015)
[7] R. Briguglio et al, Optical calibration of the ELT adaptive mirror M4: testing protocol and assessment of the measurement accuracy, AO4ELT5 (P2010)