Deformable Mirrors development in Europe - Results of the first phase of the ESO R&D program.

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ABSTRACT

ESO launched in 2016 a program to push the development of deformable mirror technologies for post focal instruments of its ELT. The focus has been put on compact DMs targeted to MOAO applications, and on XAO DMs. This resulted in 2 development contracts with ALPAO (France) and one with a consortium of IOF (Fraunhofer Institute for Applied Optics and Precision Engineering , Germany) and Physik Instrumente (PI, Germany), which have all been completed. The requirements and the used technologies will be first recalled. Then the achieved characteristics and performances will be summarized, based on the characterization on the many prototypes built during the course of these contracts. Conclusions will be finally drawn..

Keywords: Deformable Mirror, Adaptive Optics, acronyms, references

1. INTRODUCTION

With the start of construction of the ELT also the development of a suite of 1st generation instruments has started. To achieve some of the ambitious scientific goals of the ELT, even more challenging instruments are foreseen for their second generation. Two of them include dedicated adaptive optics systems for multi object adaptive optics (MOAO) and extreme adaptive optics (XAO) to hunt for earth-like planets around nearby stars. However, several key components like deformable mirrors (DM) required for MOAO and XAO are not available today. Without a good knowledge on the DMs it will not be possible to finalize the design of the associated instruments and enter a construction phase. In order to lift the uncertainties on the DMs required for the second generation ELT instruments ESO launched in the frame of the enabling technologies program a DM development activity. To progress efficiently on the design of instruments a prior knowledge of the pupil size is a crucial specification for the optical design and the mechanical layout of an AO system. Similarly the number of actuators cannot be kept open too long during the design phase. ESO launched a Research and Development activity to reduce the gap between existing devices and the needed ones, in order to reduce the uncertainties on critical properties of the DM. The program has started in 2014 with a request for information (RFI). It was possible for European companies and institutes to express their interest in participating into a DM development, to propose suitable technologies and a development path . In the first half of 2015 technical specifications for the 2 types of DMs were written by ESO[1]. One type is dubbed Compact DM with a targeted application on MOAO systems and a focus for an open loop operation. The second type is dubbed XAO DM needed for an ELT planet finder.

In a fixed price call for tender launched end 2015 companies were asked to identify critical aspects on their respective technologies and to propose a development plan addressing the identified aspects and considering the development of breadboards, demonstrating that the proposed solution is feasible and performs as expected. After the evaluation of the proposals 3 contracts were awarded.

One contract for the Compact DMs has been launched in June 2016 with ALPAO. For the XAO DM two contracts were placed in June and May 2016, one with ALPAO and one with the IOF (Fraunhofer Institute for Applied Optics and Precision Engineering) in a consortium with Physik Instrumente (PI).

1.1 DM specifications

The DM related specifications are extracted from the different pre-phase A and phase A studies of instruments incorporating post focal AO. For the compact DM the specification is based on the studies performed for the EAGLE[7] project and for the XAO-DM work for the EPICS[8] have been used. The specifications give for several parameters a range rather than a specific value. At this stage our intent is to not exclude technologies early on and to give bidders the possibility to match best their proposal to the respective technology taking into account the limitations and risks.

Description	Specification value: Compact DM	Specification value: XAO-DM
DM clear aperture	Ø30mm-100mm, goal Ø45mm.	Ø150mm-450mm, goal Ø270mm. Annular shape with 24% central obscuration
Mirror surface Flatness	<15nm rms, stability of < 21nm rms within 1h	10nm rms, goal 5nm rms, after subtraction of few low order modes (Z4 to Z11)
Actuators count within the clear aperture	2800 to 5000	11 000, goal 20 000
Actuators pitch (derived information, no specification)	0.4mm - 1.7mm	0.9mm – 3.7mm
Lowest mechanical resonance frequency (causing a mirror surface deformation)	>500Hz	>1000Hz, goal >2000Hz TBC
Actuators Stroke	>5µm (goal >8µm) (5by5 actuators)	>3µm (3by3 actuators)
Actuators resolution	-	<0.1nm goal < 0.06nm
Inter-actuator stroke	>1.3µm	>1.2µm
Small stroke settling time incl. latency of the drive electronics	250nm settling to ±10% within 700µs	50nm settling to ±10% within 150µs, goal 100µs
Hysteresis	Included in the linearity spec.	5%
Actuators non-linearity	<3% Goal <1%	<5% Goal <1%
DM surface temperature incl. Housing: deviation from ambient	<±1ºC	<±1ºC
Update frequency of the DM commands	200Hz goal 500 Hz	2500Hz goal 4000 Hz
Non-functioning actuators. The exact numbers depend on the failure mode.	10-50, goal 0	5-30, goal 0

Table 1 Summary of key specifications for the Compact and XAO DMs

For both DM types the drive electronic is part of the development. In the following some key specifications are discussed in more detail.

1.2 Particular specifications for the Compact DM

The intended use of the compact DMs sets several particular requirements. The requirement from MOAO is to increase the energy concentration in a small area like one image pixel to be able to detect fainter objects or to increase the spatial resolution. The DM will be used exclusively in open loop i.e. the WF corrections need to be applied without any feedback to the WFSs. Therefore the requirements to the actuators linearity including hysteresis are very stringent. Also the shape applied to the DM to correct for instrumental effects must be stable at least over the duration of one observation (1h) or over the entire night. The compactness of the device has a strong impact to the system design, not only the pupil size, also the design volume of the DM housing, cabling and possible needs for cooling must be minimized. The specified range of pupil diameters is limited on the lower edge by the feasibility of the optical design. Small DMs need a stronger beam compression of the 39m entrance pupil which can be achieved either by more complex optical design or by a reduction of the transmitted field of view. The upper limit of the pupil size is driven by the volume required to accommodate all components of the AO optical train. Many parallel channels are required to boost the observation efficiency; however the available volume is limited. With larger DMs only fewer observation channels can be implemented and the constraints to the compactness of the other components are increasing. In the instrument studies a feasible pupil diameter range of 30 to 100mm was identified. Exceeding the limits will eventually impact the scientific capabilities of the instrument.

1.3 Particular specifications of the XAO DM

The challenges and limits to the XAO DM are different from the compact DM ones.
For the exo-earth science the AO system needs to correct the atmospheric turbulence such that the light of the parent star can be optimally suppressed by means of a coronagraph and to enhance the visibility of a faint planet next to it. One good metric for the instrument performance for XAO instruments with coronagraphs is the contrast, i.e. the ratio of the intensity of the PSF center to the background in its vicinity. For the detection of planets in the habitable zone a good contrast very close to the parent star is required. Analysis for the EPICS instrument have shown that a very high AO system bandwidth crucially impacts this performance aspect. An update rate from 2.5 kHz up to 4 kHz will be targeted wit very fast step response of 150 µs. One limitation to achieve even higher contrast are quasi static speckles caused by small WF errors of the relay optics. One can suppress quasi static speckles by a method called electrical field conjugation[6] (EFC). By applying a static offset pattern to the WFS measurements it is possible to cancel out the static speckles in a small portion of the field. However, to be effective a very high actuator resolution of 0.1nm is required. With an optical interferometer, it will be very difficult to verify the resolution specification on the full mirror surface due to laboratory turbulence and other disturbances, however a verification on the actuators drive side will be possible. The reliability of actuators is also very important. At time of acceptance we will allow for a total of 5 nonfunctional actuators and during the 12 year lifetime 5 actuator breaks can be tolerated. Together with the drive electronics, low latency data communication, volume, power consumption and cooling issues need also to be addressed.

2. COMPACT DM

The contract granted for the work on the Compact DM was signed with ALPAO in June 2016. The proposal consisted of the development, manufacturing and testing of a full scale prototype deformable mirror. The design employs 3228 actuators within a pupil of 96mm diameter. The technology is based on the standard 1.5mm actuator pitch used in a range of commercially available ALPAO DMs with much smaller diameters and actuators counts. The proposal included also the drive electronics and the development of dedicated test bench.
The increase of size was addressed by scaling up the design of the structure of the DM.
The handling and manipulation of a large number of small components during all steps of the manufacturing generated also a challenge. This was addressed by an upscaling of manufacturing tools, the development of new integration processes and for some steps the use of robots.
After an intense phase of testing the new tools processes and devices, the compact DM could be integrated at the end of 2018. After initial tests and the calibration of the interaction matrix with the wave front sensor of the test bench all actuators of the new product could be controlled. This could be shown by drawing the ALPAO logo topped with the head of Santa Claus (Figure 1). All actuators of the DM were functional. This allowed to flatten its surface to better than 7nm rms. For key properties linked to the actuators performance like linearity, hysteresis, stroke and step response typical values for the technology were reached. The verification of the stability of the DM shape however left some uncertainties about the final system performance in this area. Limitations on the test bench did not allow to quantify the evolution of the DM shape with changing temperature and gravity to an accuracy such that clear conclusions could be drawn. The mirror shape evolution with time is dominated by actuators creeping. Similar amplitudes as described by Bitenc [2] were found but the described creep correction algorithm could not be implemented for the large number of actuators.
Nevertheless, the achieved performances are remarkably well suited for an use in an astronomical AO system using the DM in closed loop. The CDM 3228is the DM with the highest actuator count ever manufactured in Europe for astronomical applications.

Next steps in the development could be a more extensive characterization of the thermo-mechanical behavior of the DM, improving its initial shape at rest and extending to larger dimensions the high stability option available for smaller size DMs.

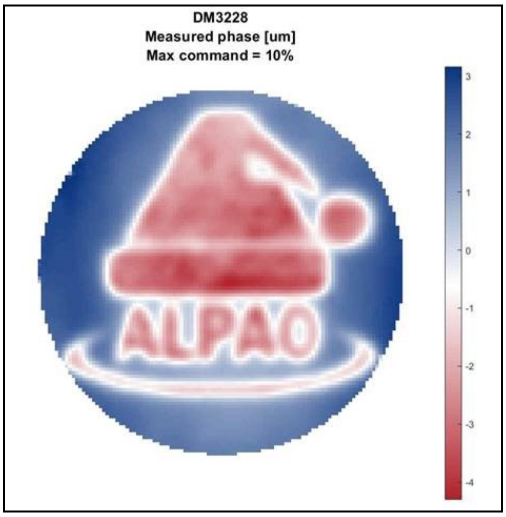

Figure 1 Phase map of the DM3228 after integration and calibration measured in December 2018.

3. XAO DM

The gap in actuator count between existing deformable mirrors and the need for an XAO system for the ELT is even larger than for the CDM. When ESO launched the call for proposals it was entirely unclear if existing technologies could be extended and scaled to the required DM size, actuators count and density. The increase of the system complexity poses strong challenges to the density of components and connections. To overcome these challenges and to get an more accurate estimate on the required efforts to build an XAO DM, 2 contracts were granted: one with ALPAO and one with the IOF (Fraunhofer Institute for Applied Optics and Precision Engineering) in a consortium with Physik Instrumente (PI).

3.1 ALPAO

The proposal made by ALPAO consisted of breadboards specifically addressing key challenges. One was to scale the technology to the large size and actuators counts, the other was the feasibility of a large membrane to be used for the mirror face sheet. If the mirror design is based on the standard ALPAO 1.5mm actuator pitch a membrane with ~200mm diameter is required. At the contract kick-off, the feasibility of large membranes was not proven and the manufacturing process used for the smaller ALPAO DMs could not be scaled up to manufacture a 200mm membrane. New processes had to be developed.

A parallel development activity focused on the design and manufacturing of fast actuators with 1mm pitch. With a smaller actuator pitch it would be possible to accommodate the required actuators on a smaller membrane which could be manufactured by pushing the currently used process to its size limits. The drive electronics posed also a challenge. To avoid issues with numerous connections between the actuators and the interface to the real time computer, integrated DM drive electronics were developed. This set strong constraints on the size of the components and the heat dissipation.

The manufacturing of large membranes was successfully concluded: the identified processes were suitable and could be applied to manufacture few prototypes with a 200 mm diameter. The testing and characterization has shown that these large membranes could be used in a deformable mirror.

The development of the smaller actuators required a down sizing of already small components. Feasibility and efficiency of the force generation had to be prototyped. After successful testing of individual actuators, a DM with 97 actuators was assembled to verify the stroke and dynamical properties. Measured performance of both parameters were matching the requirements. The handling and integration of the small size of the components required more efforts during the integration. With the proven feasibility of very large membranes there was no need to push the 1mm pitch technology further and the already proven 1.5mm pitch actuators is now used as baseline.

For the electronics several possible solutions were studied to more detail. One solution could be found to comply to the combination of the requirements for high actuators resolution, fast update rate, small volume and small thermal dissipation. Based on this solution a prototype was developed and tested: key requirements such as resolution, latency, noise and crosstalk were successfully verified. The prototyped solution seems to be suitable for a scaling to a larger number of channels.

Following the successful demonstration of large membrane availability, and integrated drive electronics performance, a conceptual design of the XAO DM system could be worked out (Figure 2)

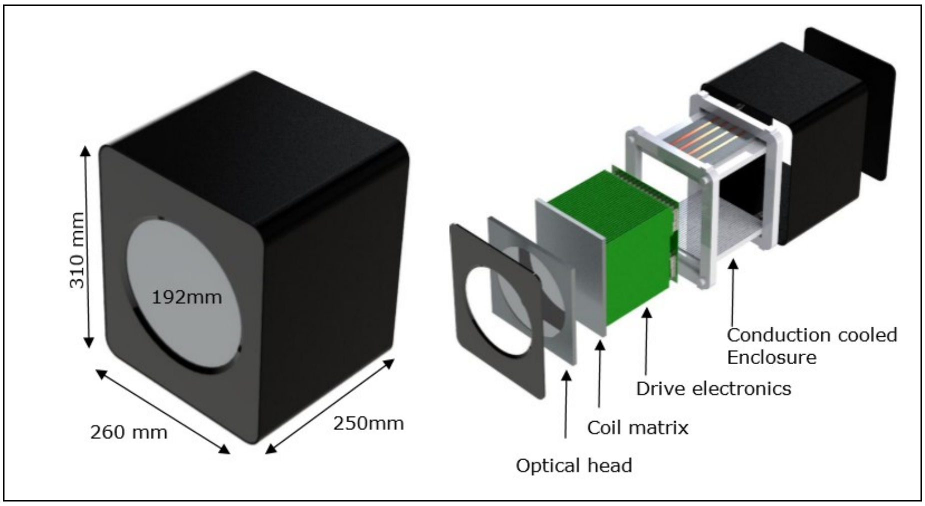

Figure 2 Conceptual design of the ALAPO-XAO DM

According to the concept the DM assembly hosts all components required to deform the mirror shape including its drive electronics, and is wrapped into an housing requiring only connections for power, cooling and DM commands/communication (through fibers).

The next steps for the development on a XAO system could be further work on the dynamic properties of the actuators e.g. on the control side by using signal shaping. An optimization and tradeoff of the linked properties of actuators stroke, speed and power dissipation is required. Finally, more work on the thermal design and modeling is required to insure that the DM meets the requirements about the surface temperature and heat dissipation to its environment. Then, key developments could be prototyped in an intermediate or full size DM system.

3.2 Consortium IOF with Physik Instrumente (PI)

The proposal for the XAO DM by IOF-Physik Instrumente (PI) consortium is based on the PICMA® stack actuators assembled in a mechanical structure allowing to replace actuators in case of failure.

It pursuits the development of actuator modules with a moderate number of piezoelectric stacks that are to be integrated into the deformable mirror. Assembling the large DM by making use of preassembled actuator modules provides several benefits. The main advantage is the availability of precisely manufactured preassembled actuator modules that are individually inspected to guarantee for the highest quality. Furthermore, the exchangeability of defective actuators by their corresponding actuator modules is possible, leading to the name of the deformable mirror: SWAP DM. As the piezoelectric actuators are sensitive against tensile load, a spring preload can insure the required lifetime of the actuators as well as the push-pull capability required for the deformation of the DM surface.

The concept is illustrated in Figure 3. A piezoelectric stack actuator (e) is preloaded by a spring (d). Between both is a pin (b), which transmits the translation to the mirror (a). The actuator bottom is fixed on an actuator module base (f) which is screwed into the support structure (c). The actuator module base (f) offers bores for the actuator wiring (g).

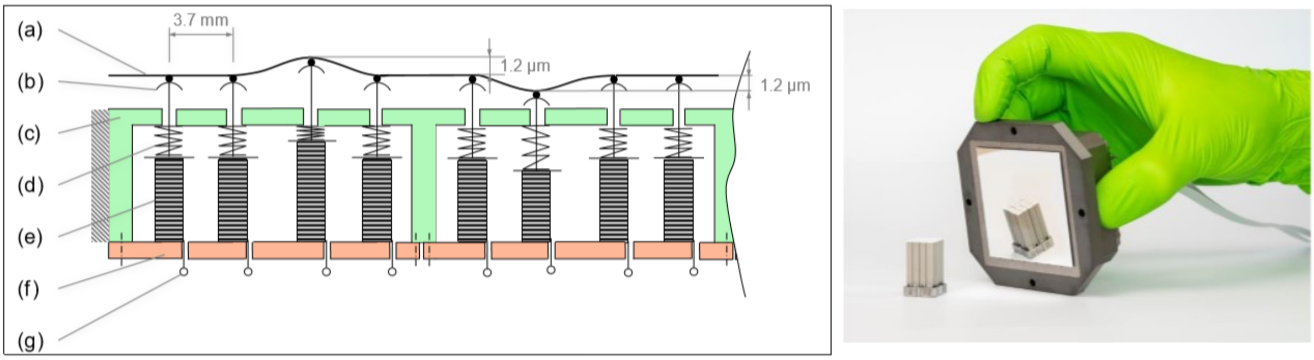

Figure 3 Left: Schematic design of the XAO DM; (a) mirror, (b) pin, (c) support structure, (d) spring, (e) piezoelectric stack, (f) actuator module base plate, (g) wiring. Right: Picture of the assembled SWAP prototype with 50 x 50 mm deformable substrate and 144 actuators. One 4x4 actuator module is displayed in the front.

The development activities were grouped in 5 breadboards and addressing the following aspects: A) development and manufacturing of the piezo actuator modules, drive electronics, and electrical contacting. B) lifetime testing of the actuators under the specific load and environmental conditions. C) Design and prototyping of mirror-pin interface. D) development of the procedures and tools for mounting the mirror face sheet to the pin array. E) Integration and test of the previously developed components into a prototype DM.

The manufacturing of the components and integration of the prototype DM involved the development and validation of dedicated integration tools and procedures. On the prototype the functioning and key performances of the actuators could be characterized. The development phase included also a conceptual design of a full size SWAP DM and a proposal for the next development steps in order to increase the technology readiness. They cover activities on design refinement and testing of the actuators module exchange, improvement of the mechanical connection between the mirror face sheet and the pins and the manufacturing and integration of a full sized optical face sheet. It is also part of this proposal to develop a full sized reference body and manufacture a sufficient number of actuators to populate a representative part of the DM.

4. SUMMARY

The high level goals of the first phase of the DM technologies development have been successfully reached.

The feasibility of a high actuator count Compact DM suitable for ELT MOAO-based instruments has been demonstrated through the assembly and test of a fully functional prototype. There is a clear understanding on the remaining steps and work to achieve a full compliance to the ESO's demanding requirements.

For the XAO, critical and potentially show stopping elements could be successfully prototyped. This was an important step to reduce the technological risks, paving the road towards the availability of DMs for the future ELT's XAO systems. Two different technologies could be pushed forward. With the parallel elaboration of conceptual designs, an understanding of the required next activities and involved efforts was gained. These are valuable inputs for the definition of the next steps of the XAO DMs development.

In conclusion, ESO would like to thank ALPAO, IOF and Physik Instrumente (PI) together with all their team members for the effort invested in order to help in achieving the very challenging path towards the availability of DMs requested by the development of the future ELT's instruments.

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