Deformable Mirror requirements for & feedbacks from VLT & E-ELT

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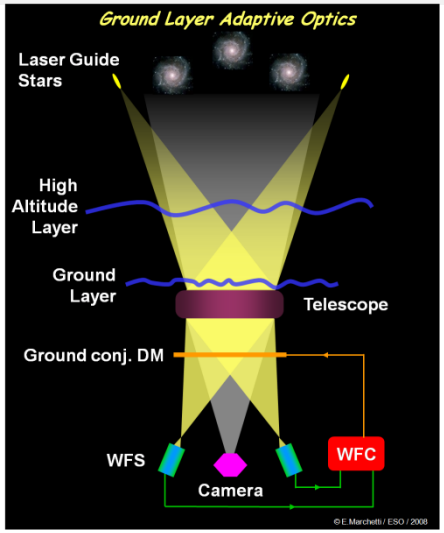
Outlines

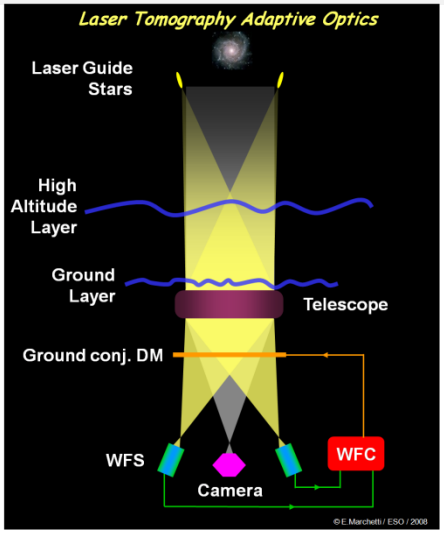
- Overview of potential E-ELT AO systems
- Deformable Mirror (DM) requirements
- Experience & feedback with VLT AO systems
  - Stacked Array DMs
  - Bimorph DMs
  - Large & small voice-coil actuator DMs
  - Micro-Electro-Mechanical Systems DMs
- Conclusion

Overview of different AO types

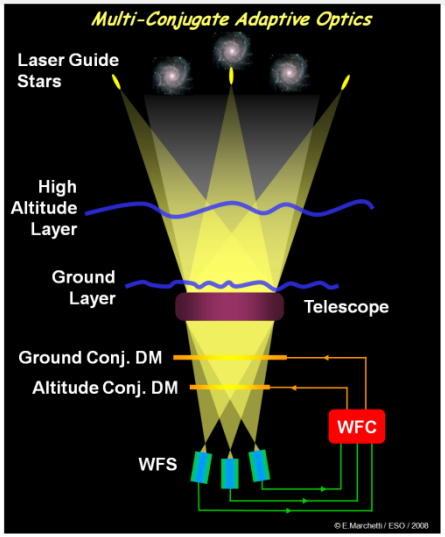
GLAO-LGS



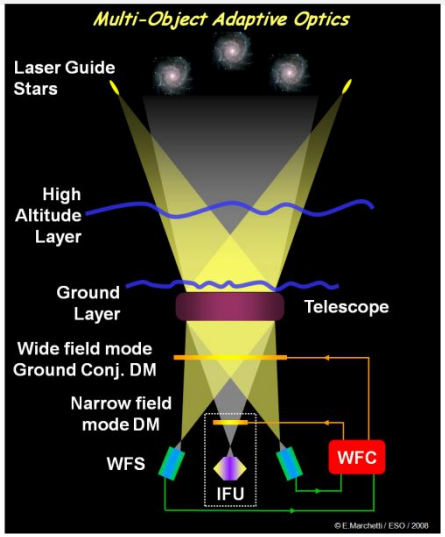
LTAO: ATLAS



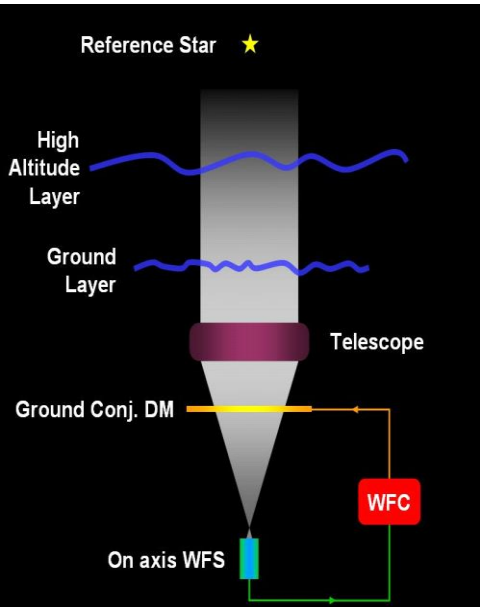
MCAO:MAORY



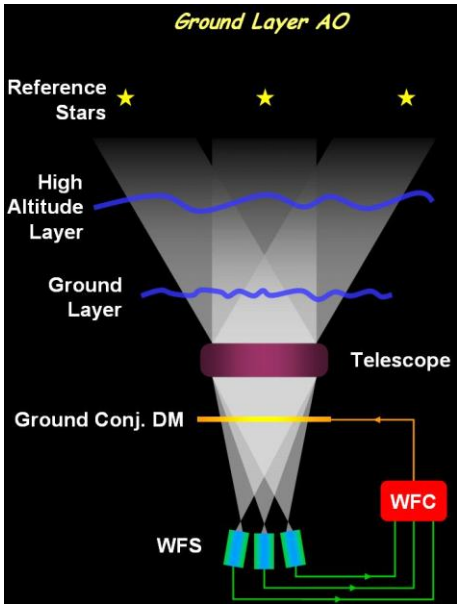
MOAO:EAGLE



SCAO & XAO: EPICS

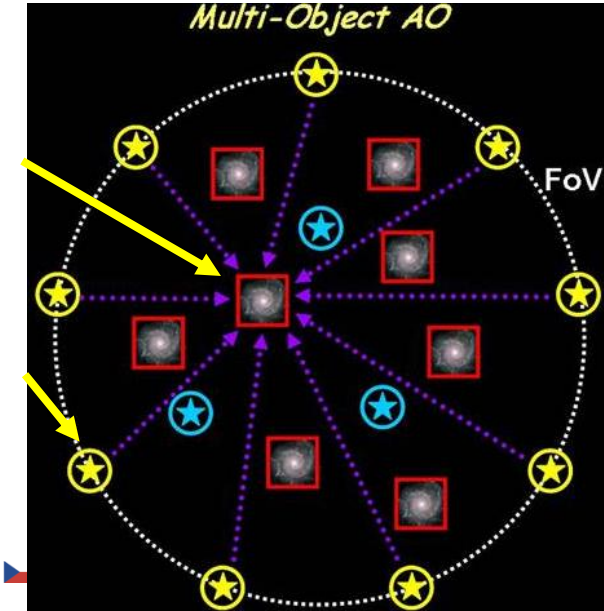


GLAO-NGS

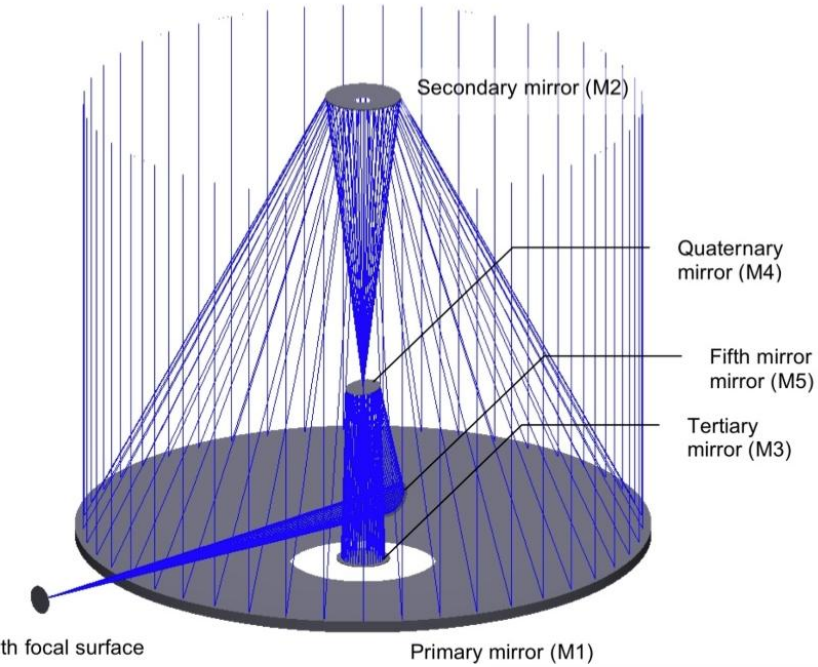


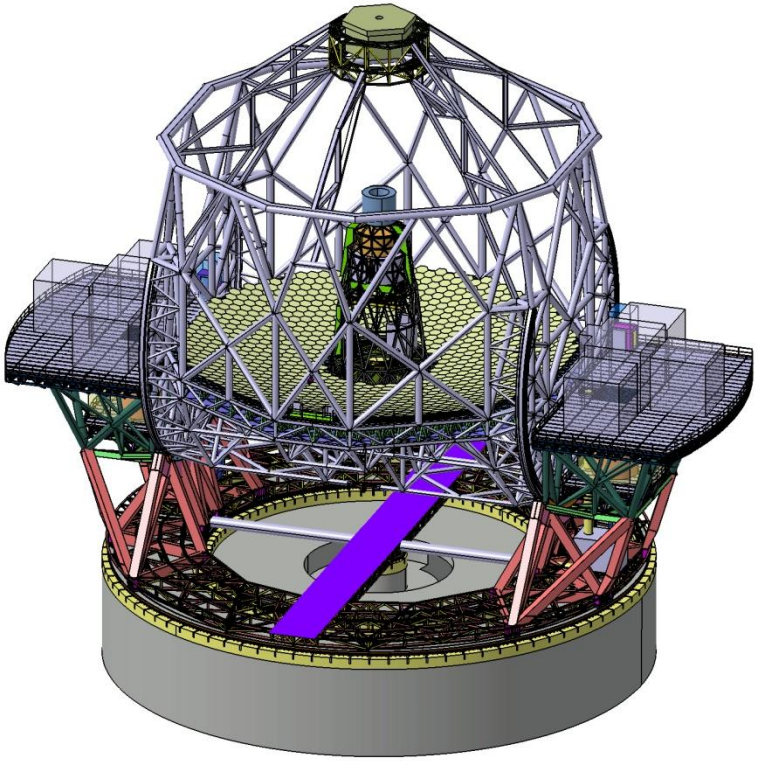
Few" IFU

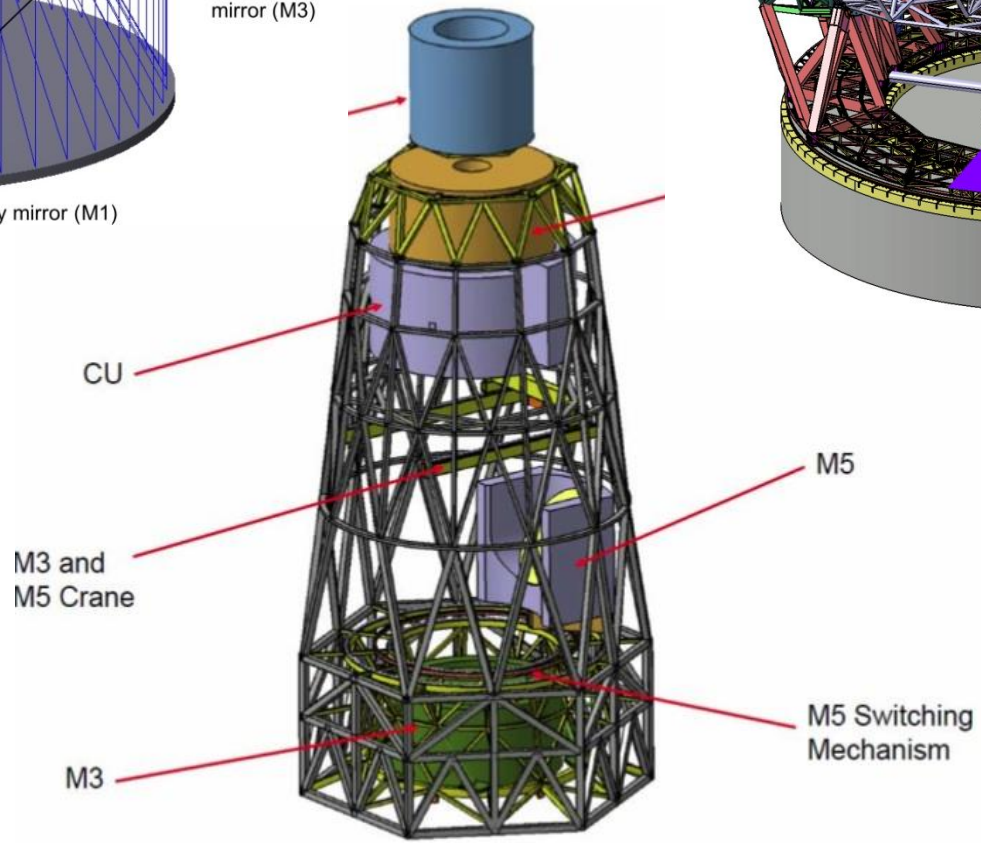
6-8 LGSs in Ø 7.2'



E-ELT Ground Layer AO

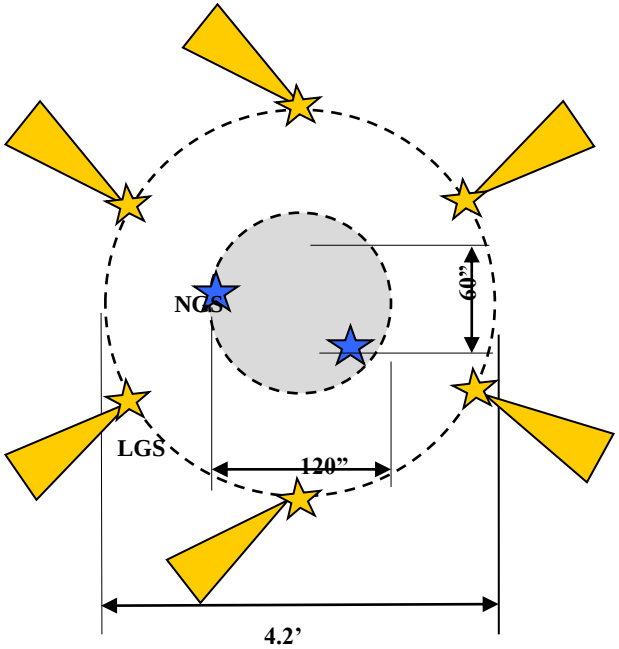


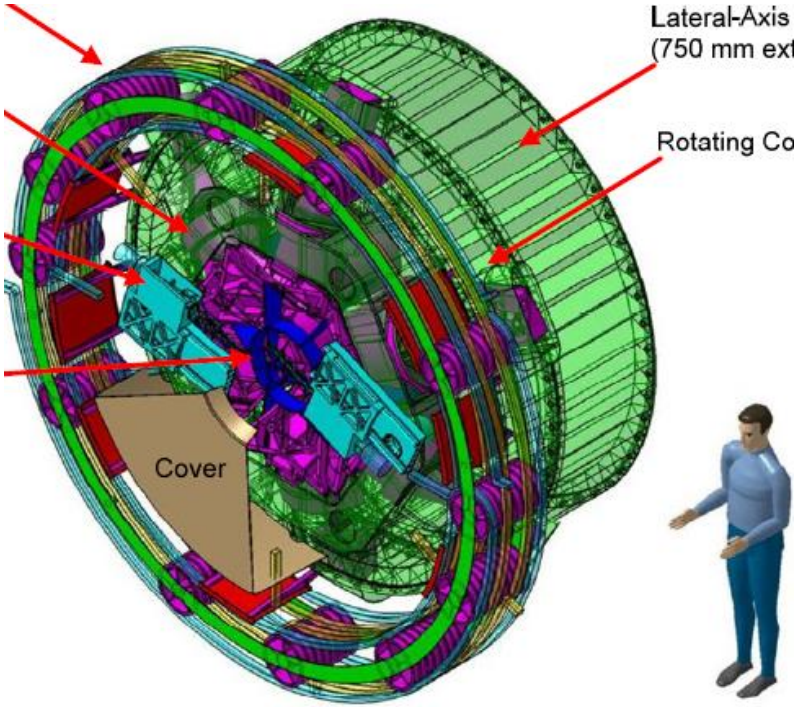




E-ELT Laser Tomography AO

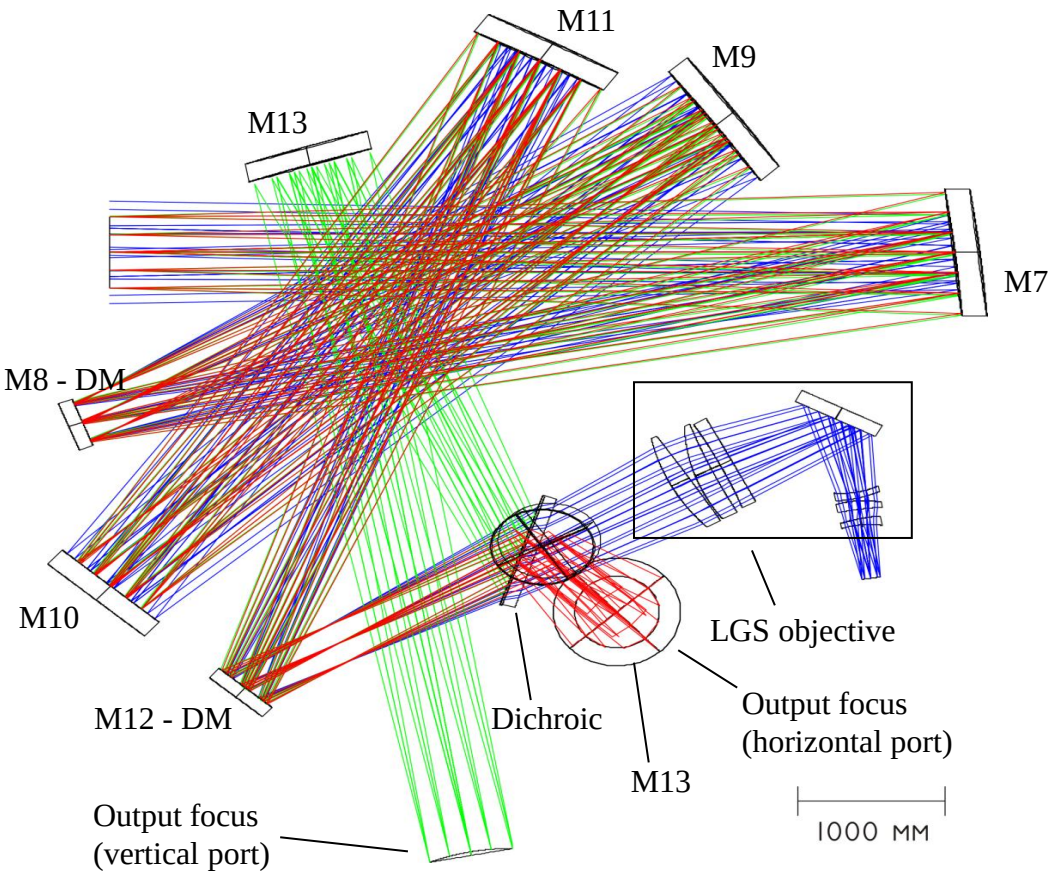
- 6 Laser Guide stars side launched
- 2 IR Natural Guide Star **corrected with µDM**
- Very high quality images (S.R. >50% in K) over ~30"FoV
- Uses the **telescope adaptive mirror**, simple design, >90% transmission

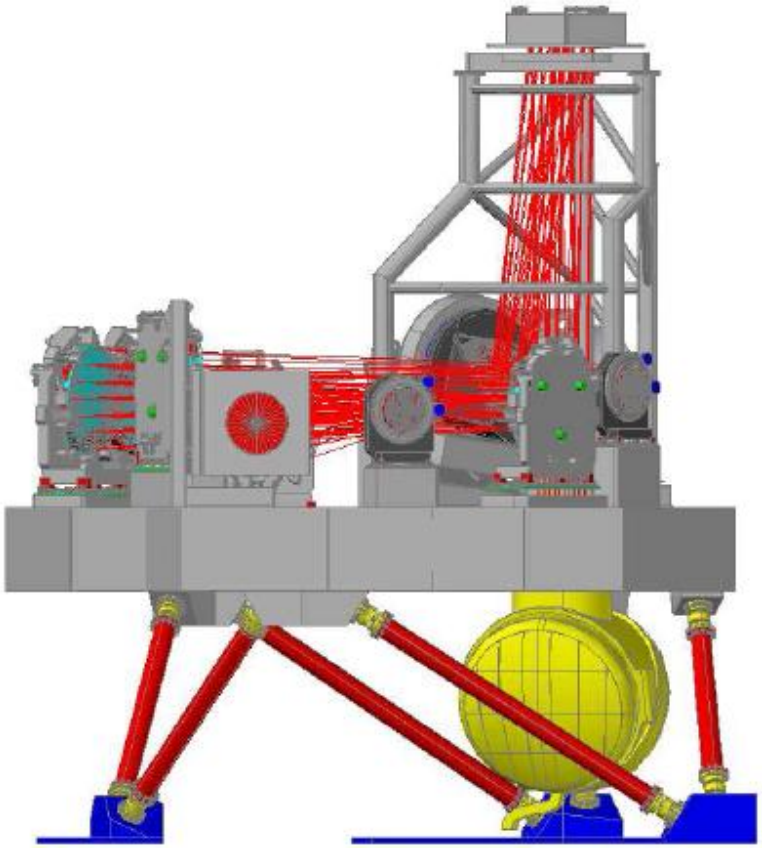




E-ELT Multi Conjugate AO: MAORY

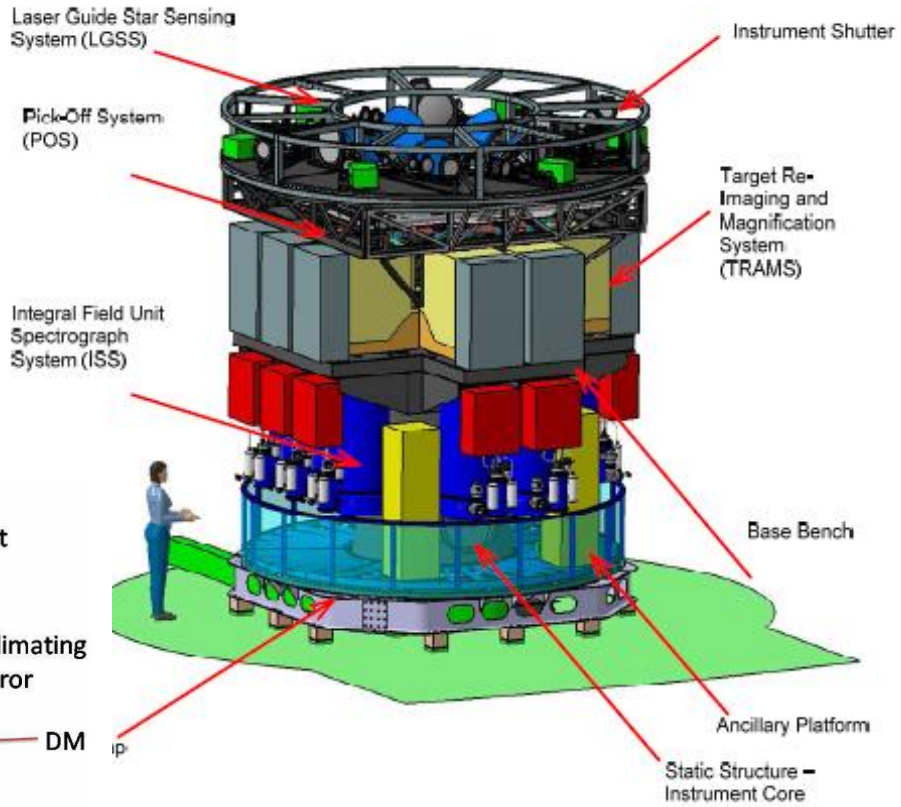
- 6 LGSs side launched; 3 NGSs (IR WFSs)
- 0.6 μm < λ < 2.4 μm
- S.R. >50% in K over 2'
- **MAORY DMs conjugated at 4km, 12.7km**

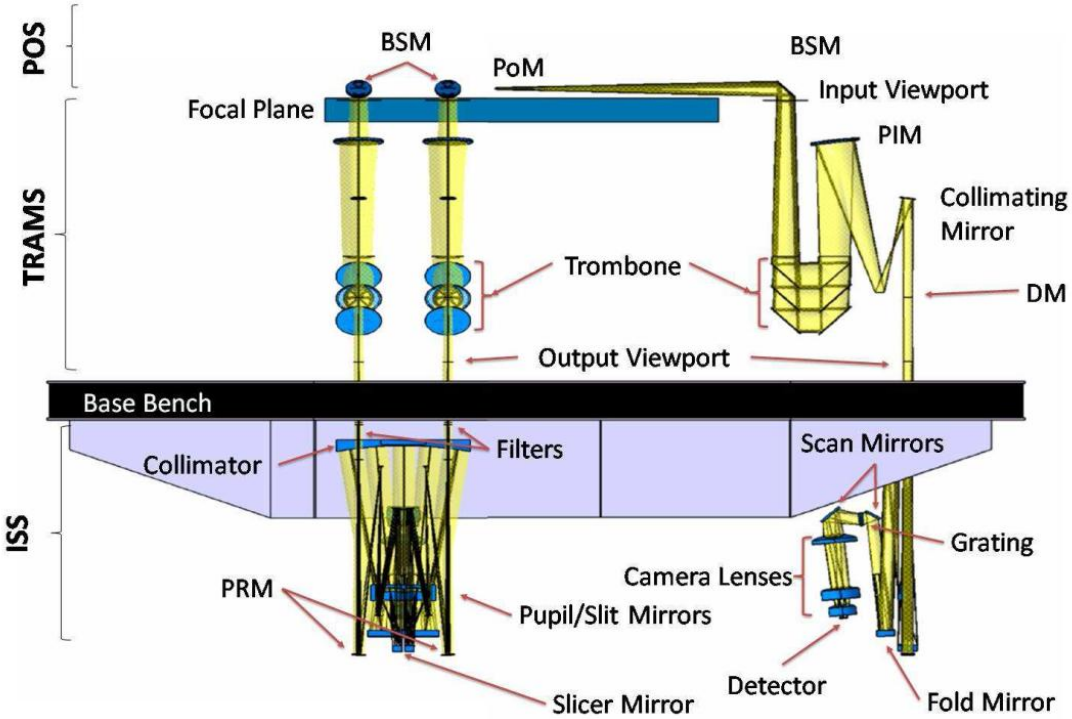




E-ELT Multi Object AO

- 6 Laser Guide Stars + 5 NGS
- Adaptive M4 for Large FoV correction
- Near-infrared: 0.8-2.45mm
- Patrol field: 38arcmin^2
- 10-20?-MOAO assisted IFUs **equipped with 64x64 act DM**.





Adaptive Optics for EPICS

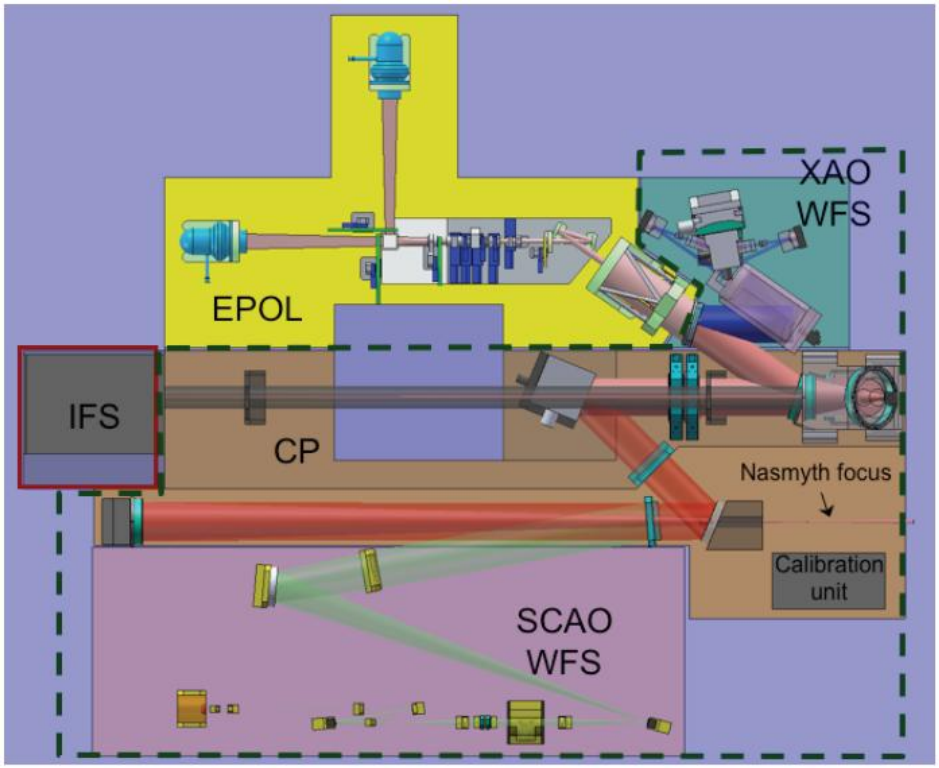
Superb XAO and waveferont control

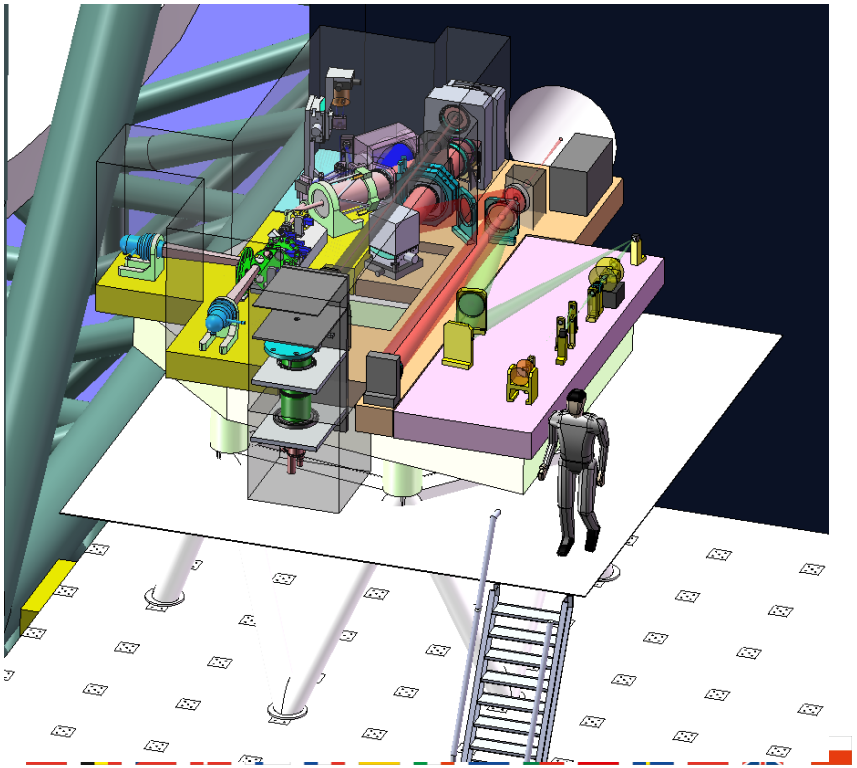
Serial SCAO **using EELT M4** and **internal XAO** with very high Strehl (90% in H-band)
Turbulence residual halo ~10^{-5} at 30mas <10^{-6} close to the AO correction radius
Quasi-static speckles at a similar level than AO residuals through phase-diversity

IFS 0.95-1.65µm
FOV: 0.8'' x 0.8''/2.33mas
0.8'' x 0.014'' long slit
R = 125, 1400 and 20000

Contrast ratios – 10^{-8} – few 10^{-10}

EPOL 0.6-0.9µm
Coronagraphic polarimeter
FOV: 2'' x 2''/1.5mas





Basic principles for DM requirements

$$\sigma_{res}^2 = \sigma_{fitting}^2 + \sigma_{temporal}^2 + \sigma_{noise}^2 + \sigma_{tomo}^2 + \sigma_{misc}^2$$

Number of actuators $\sigma_{fitting}^2 = 0.3 \left(D / r_0 \right)^{5/3} N^{-5/6}$

Response time $\sigma_{temporal}^2 = \left(\tau / \tau_0 \right)^{5/3}$ $\tau_0 = 0.314 \, r_0 / v$

Stroke $\delta = \frac{3\lambda}{2\pi} \sqrt{0.134} \left(D / r_0 \right)^{5/6}$

Inter actuator pitch AO optical design

DM technology

Temperature insensitive

Reliable (MTBF > 5 years) – maintainable (actuator replacement)

Overview of DM requirements

	8m class telescope			40m class telescope			
	SCAO	MCAO	XAO	SCAO	MCAO	LTAO & MOAO	XAO
number of actuators	200-400	200-400	1200	5 - 6000	2.5-3500 iv)	1-4000	<30000
pitch (mm)	30[i)] / -[ii)]	-[ii)]	- [ii)]	30[i)] / 1.5 to 5	6 to 8	1-2	1-2
mechanical stroke (mm)	10	6 to 10	2 or 10	40 to 80 **2-3 (tweeter)**	5-10	5-6 **Open loop**	2 to 3
control bandwidth[iii)] (Hz)	40-80	40-80	110	40-80	40- 80	20-30	110

i) 30 mm pitch is given for a 1m class secondary deformable mirror

ii) there is no particular requirement for this parameter: it depends on the system design and constraints

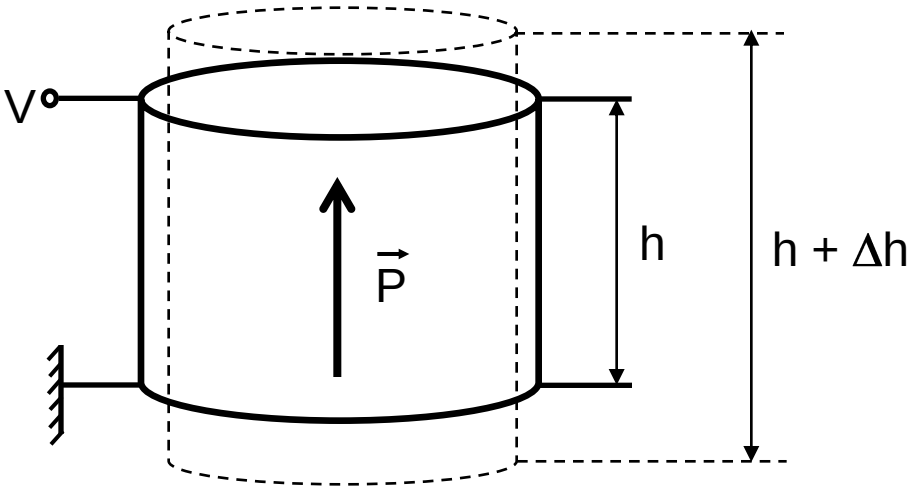
iii) within this bandwidth, the phase lag of the DM transfer function has to be smaller than 5 degrees

iv) Some users may want to operate this DM a -30C

VLT experience with DM technologies so far (NOT EXHAUSTIVE)

- NACO (1 SCAO syst.)➔ 189 actuator piezo DM (CILAS)
- MACAO (6 SCAO syst.)➔ 60 act. piezo bimorph DM (CILAS)
- MAD (1 MCAO syst.) ➔ 60 act. piezo bimorph DM (CILAS)
- High Order Test bench:➔ 1024 act. MEMs DM (Boston MM)
- PEACE test bench: ➔ 277 electro-mag. DM (ALPAO)
- SPHERE: ➔ 1370 act. piezo DM (CILAS)
- VLT Adaptive Optics Facility:➔ 1170 act. voice coil DM (1.1m) (MG-ADS)

Ferroelectric material



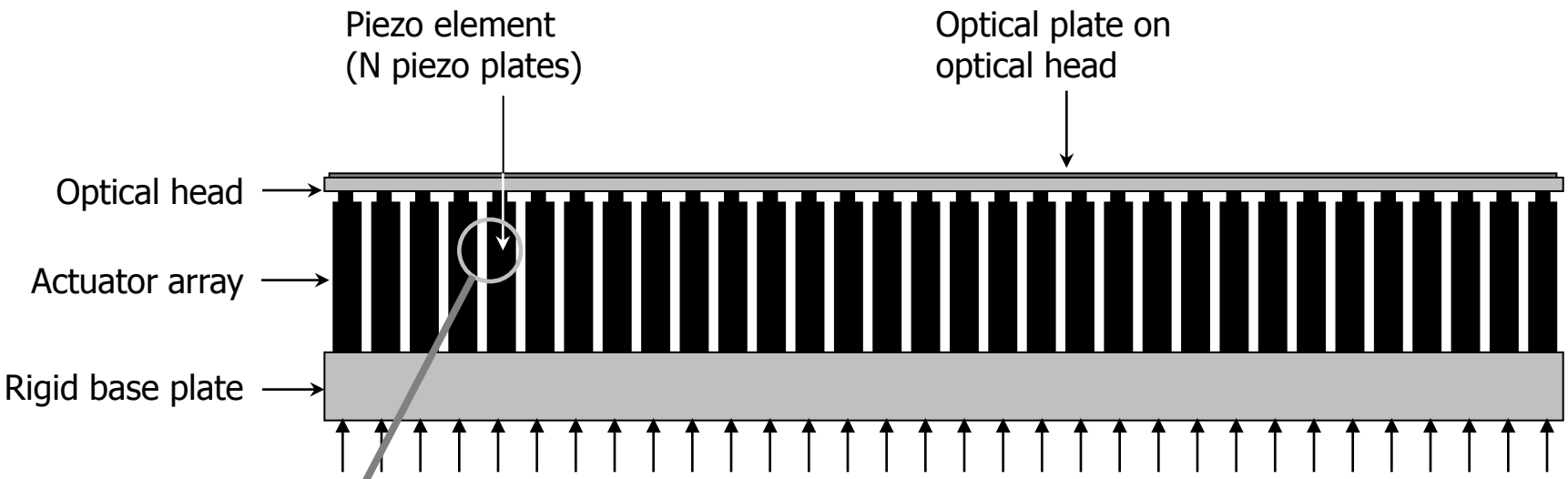
- Longitudinal effect
  - Piezoelectric material
    - Lead zirconate titanate (PZT)

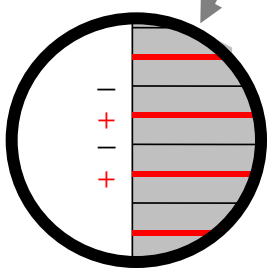
$$\Delta h = d_{33} V$$

  - Electrostrictive material
    - Lead magnesium niobate (PMN)

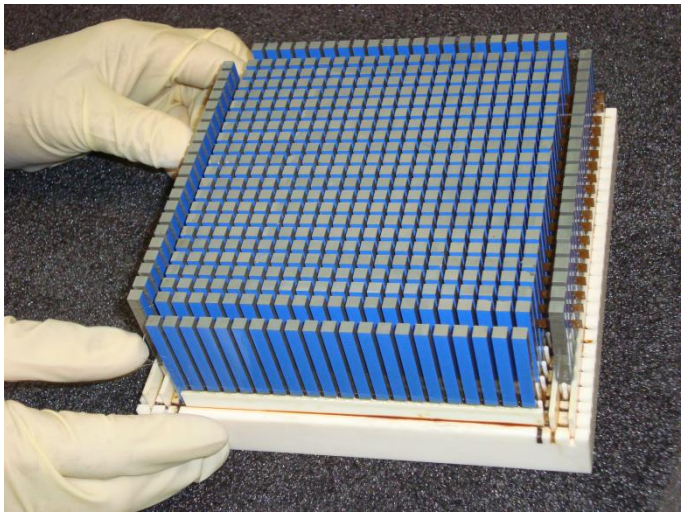
$$\Delta h = d_{33} \frac{V^2}{h}$$

Stacked Array DMs



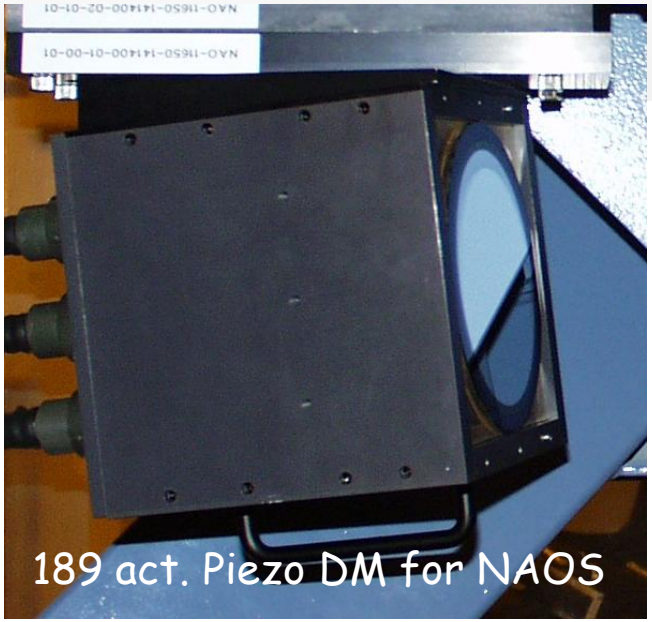


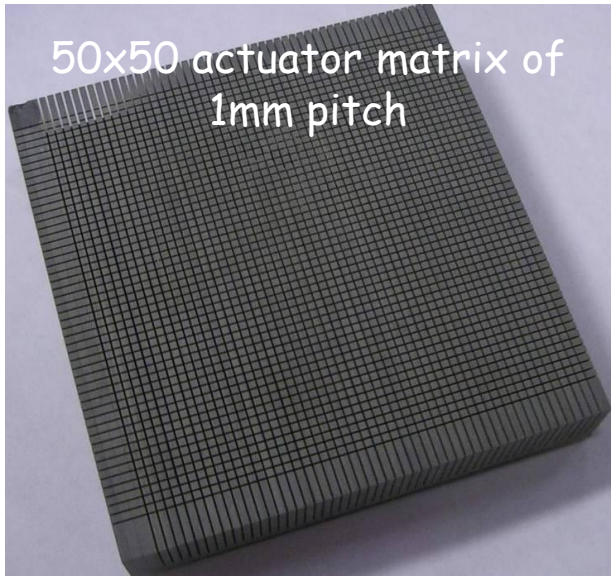
Maximum stroke of an actuator: $\delta = N\ d33\ V$
N: number of piezo plates
d33: piezo coefficient (µm/V)
V: applied voltage (V)



(courtesy CILAS)

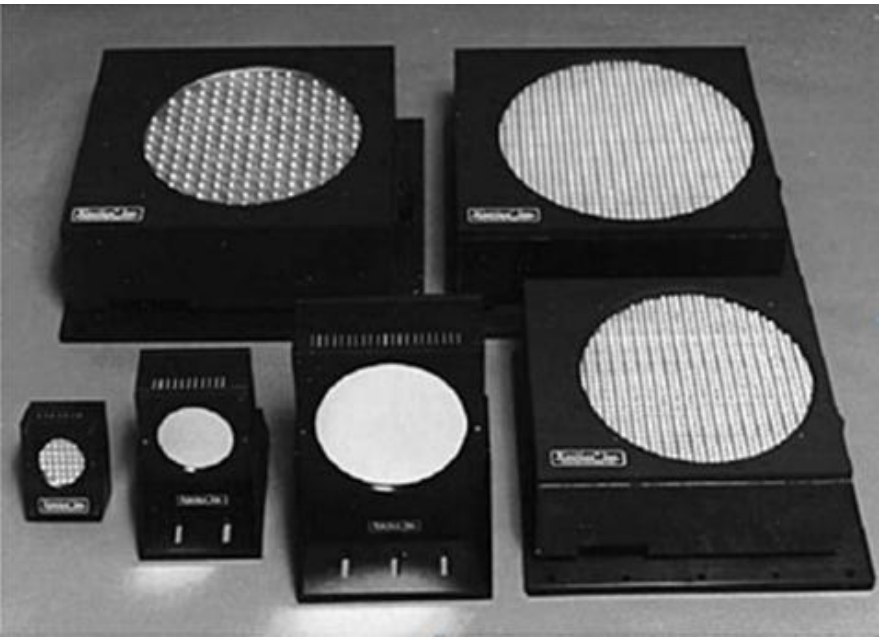
Development of Piezo DM technology





PMN DM (from Xinetics)

(Northrop Grumman)



7 mm pitch – 3 to 8 μm stroke

37, 97, 177, 241, 349, 577 or 941 actuators

5 mm pitch – 3 to 8 μm stroke

37, 97, 349 or 577 actuators

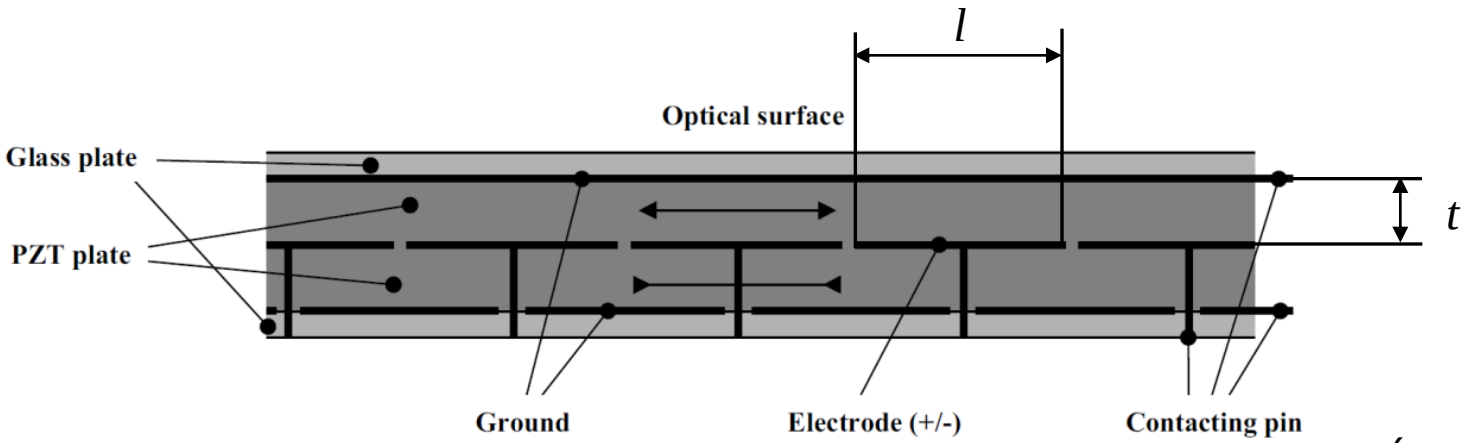
1 mm pitch – 0.5 μm stroke

64x64, 32x32, 48x48 actuators

Pros/Cons of Stacked Array DMs

- Cons
  - High drive voltages (0-150V or ±400 V)
    - Bulky electronics – large cable bundles
  - Creep, hysteresis
  - Complex manufacturing process
    - Manufacturing time / cost & risk
- Pros
  - “Relative” mature technology
  - High stiffness & High reliability
  - Large stroke – good accuracy
  - High resonant frequencies; applicable to many AO systems
  - Flexibility in actuator count and geometry

Bimorph DMs

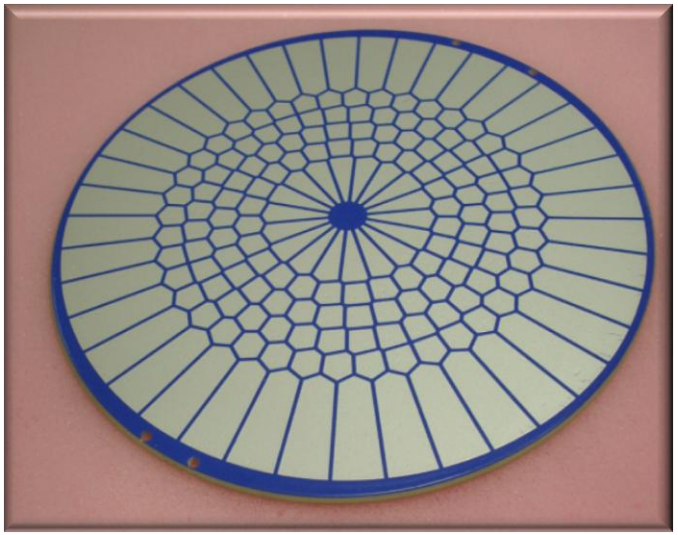


(courtesy CILAS)

$$\Delta l = \pm V\, d_{31} \frac{l}{t} \quad \Rightarrow \quad R = \frac{t\, l}{2\, \Delta l} \quad \Rightarrow \quad \delta = \frac{l^2}{4t^2} d_{31}\, V$$

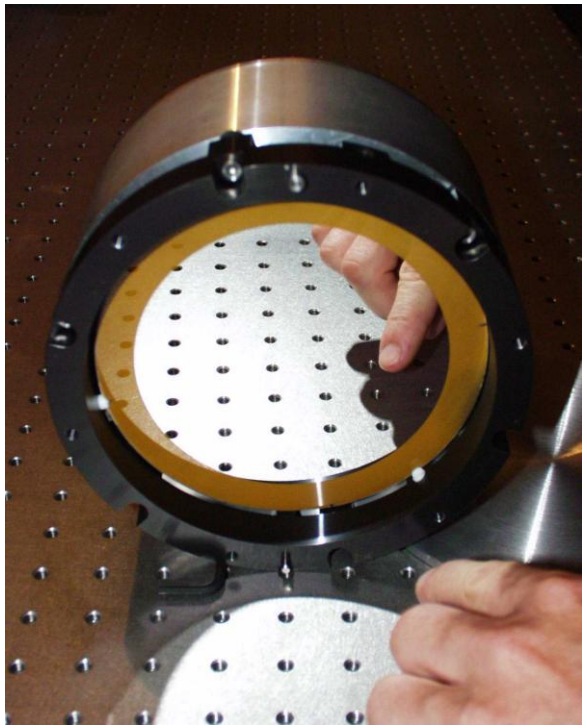
- Competition between longitudinal and transverse effect: $l \geq 4t$
- Resonance frequencies
  - DM (circular plate): few kHz
  - 3 point supporting mount: few hundred Hz

Bimorph piezo Deformable mirrors



SUBARU 188 electrode
Bimorph DM

(courtesy CILAS)

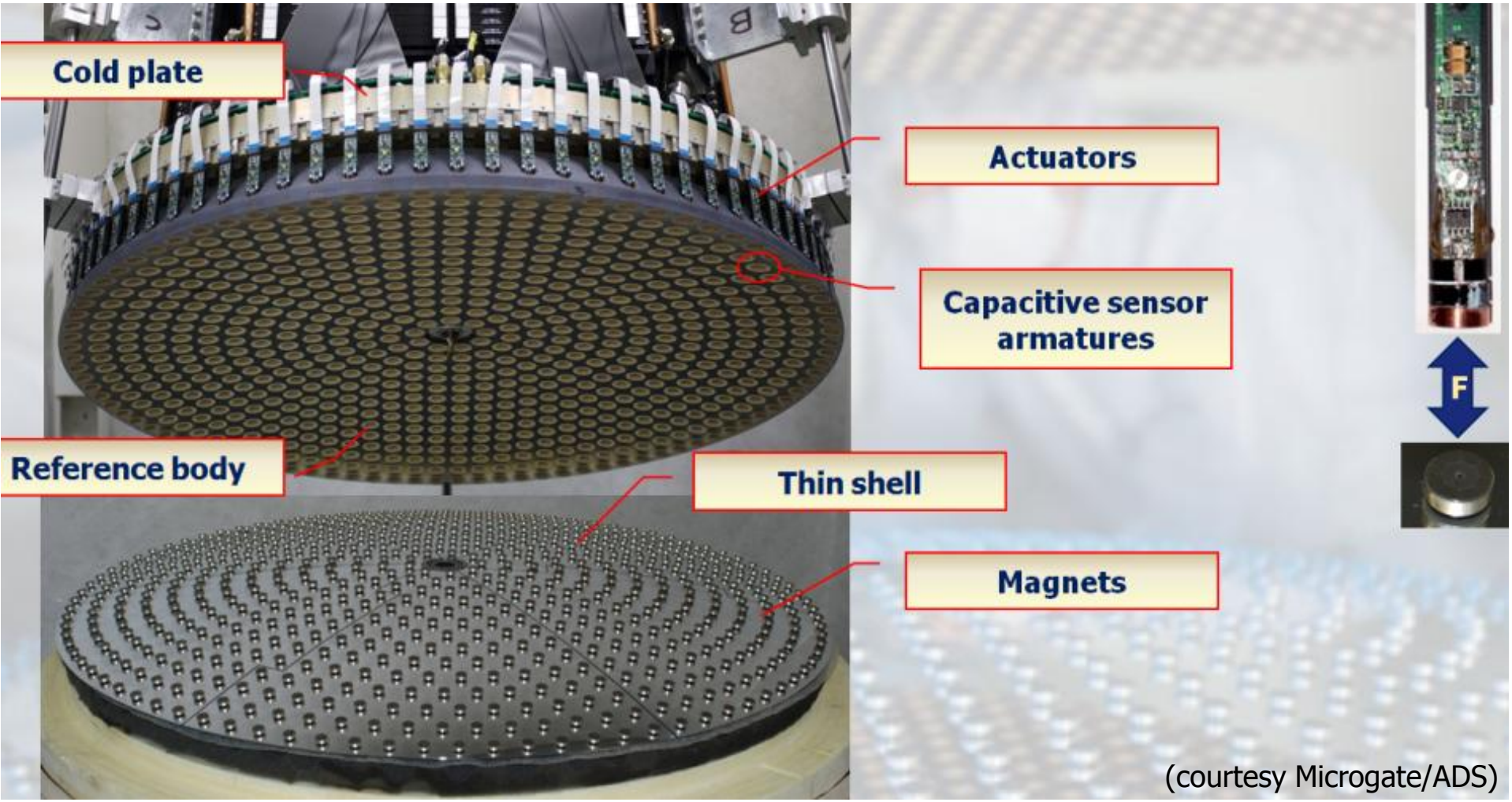


MACAO bimorph DMs
60 & 100 mm diameter
60 electrodes

Pros/Cons of Bimorph DMs

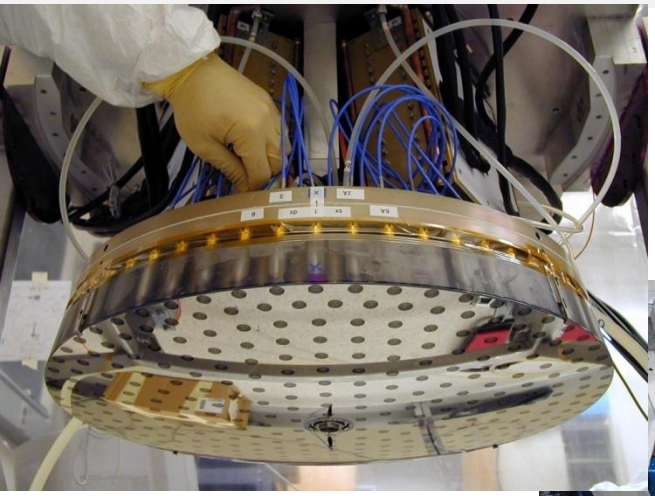
- Cons
  - High drive voltages (±400 V); bulky Drive electronics
  - Creep, hysteresis
  - Few hundred Hz resonant frequencies (DM mount)
  - Number of actuators < 200 to 300
  - No very small and large size (beyond 100 mm)
  - Needs to be mounted on Tip-tilt mount
- Pros
  - High reliability
  - Large stroke – good accuracy
  - Reasonable manufacturing time
  - Moderate cost

Large Voice coil actuator DMs



(courtesy Microgate/ADS)

Large voice coil DM



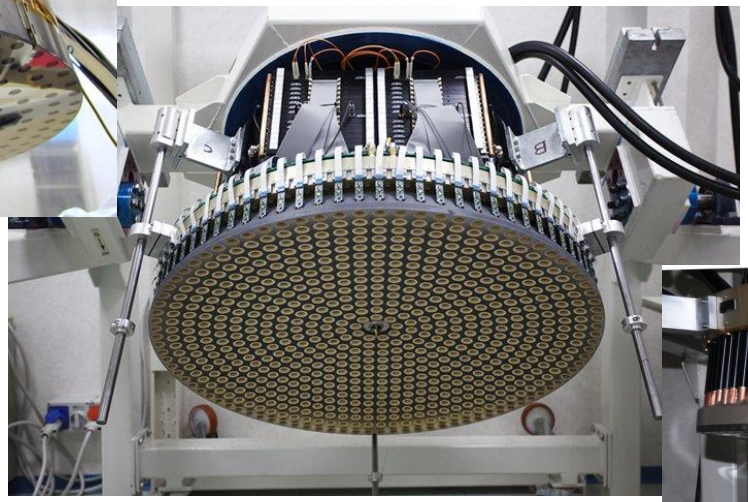
MMT ASM

640 mm diameter

2 mm thin shell

336 actuator

1.3 ms response time



LBT ASM

910 mm diameter

1.6 mm thin shell

672 actuator

< 1 ms response time

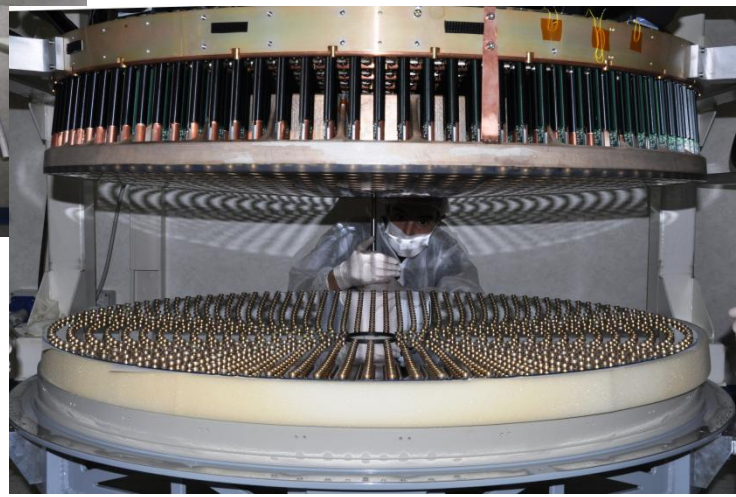
VLT DSM

1120 mm diameter

2 mm thin shell

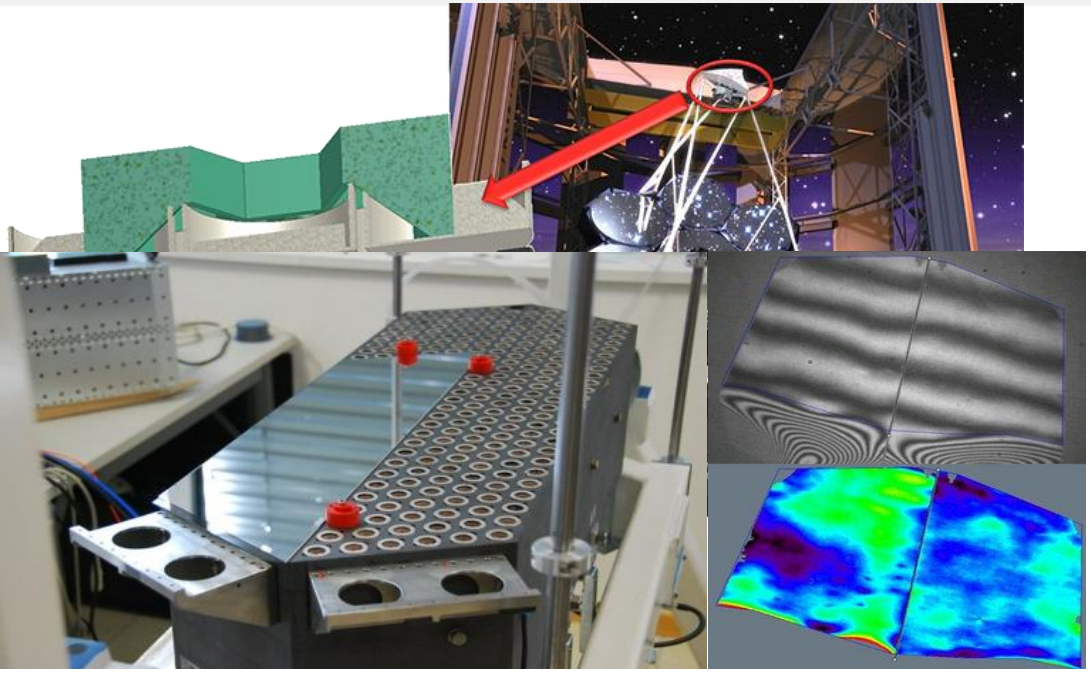
1170 actuator

1 ms response time



(courtesy Microgate/ADS)

Microgate and ADS International



E-ELT M4 prototype

Optical quality: 20 nm rms

E-ELT M4 DM

2400 mm diameter

5000 actuators

120 μm stroke

Segmented concept: 6 petals

Preliminary Design Consolidation on-going

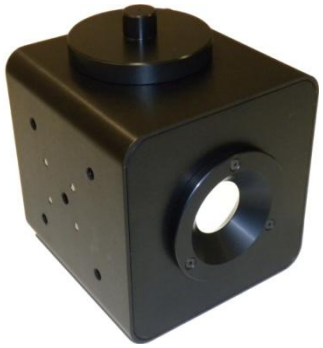
(courtesy Microgate/ADS)

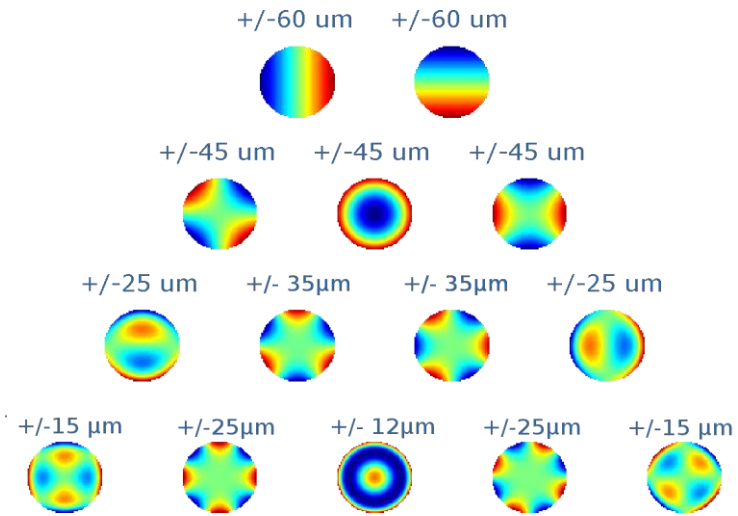
Pros/Cons of large Voice Coil DMs

- Cons
  - Large pitch (30mm): only suitable for secondary mirrors
  - Actuator power dissipation
  - Thin shell breakage risks
    - Thin shell manufacturing, DM integration, re-coating
  - Extremely complex manufacturing process
    - Manufacturing time / cost; bulky
- Pros
  - Reliability and maintainability (actuator replacement…)
  - Very large stroke (tip-tilt compensation) – good accuracy
  - Long term stability (no creep effect)
  - Short response time
  - Suitable for Adaptive Telescope

Small voice coil deformable mirror

	ALPAO Hi-Speed DM277-15
Clear aperture size	24.5 mm
Number of actuators	277
Distance between two actuators	1.5mm
Geometry of the actuators	Square Grid
Mirror surface quality in closed loop	Error < 7.0 nm RMS
Wavefront tip/tilt stroke (Peak-to-Valley)	>+/- 60µm
Wavefront astigmatism and focus (Peak-to-Valley)	> +/- 45µm
Wavefront inter-actuator stroke	> 3.0 µm
Non linearity errors	< 3%
Settling time (at +/- 5%)	1 ms
Coating	Silver Protected
Operating Temperature	15 - 35 °C
Software interface available for:	C/C++, Matlab, Labview
Hardware interface	PCI I/O Board



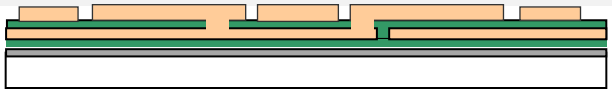


Pros/Cons of small Voice Coil DMs

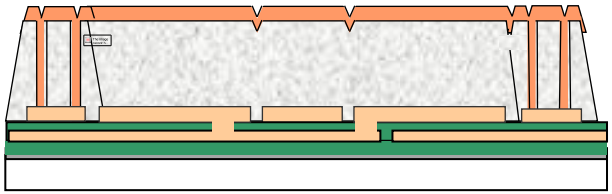
- Cons
  - Small pitch (1.5-2.5 mm) & small DM size (not for ELT MCAO)
  - Limited number of actuators➔ membrane foil size
  - Not yet suitable for open loop AO (no feedback metrology)

- Pros
  - Small size suitable for compact AO system
  - Relative compact drive electronics➔ could be better
  - Reliability and easy to set-up
  - Very large stroke
  - Long term stability (no creep effect)
  - Good response time

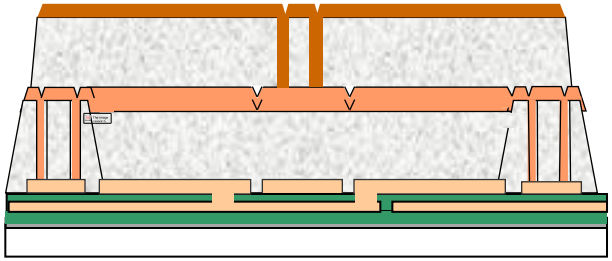
MEMS DMs



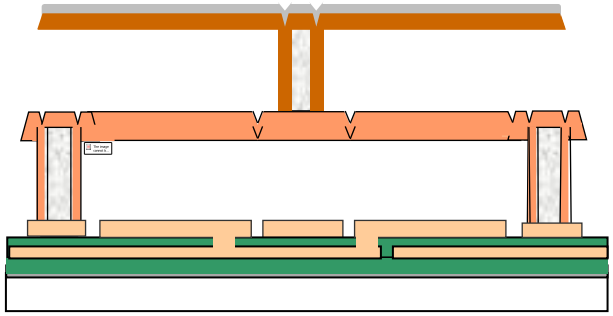
Electrodes & wire traces:
Deposit, pattern, etch alternating layers polysilicon & silicon nitride



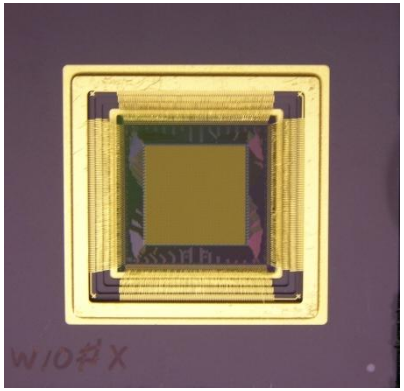
Actuator array:
Deposit, pattern, etch sacrificial oxide and 3rd polysilicon film



Mirror membrane:
Deposit, pattern, etch 2nd sacrificial oxide and 4th Polysilicon film



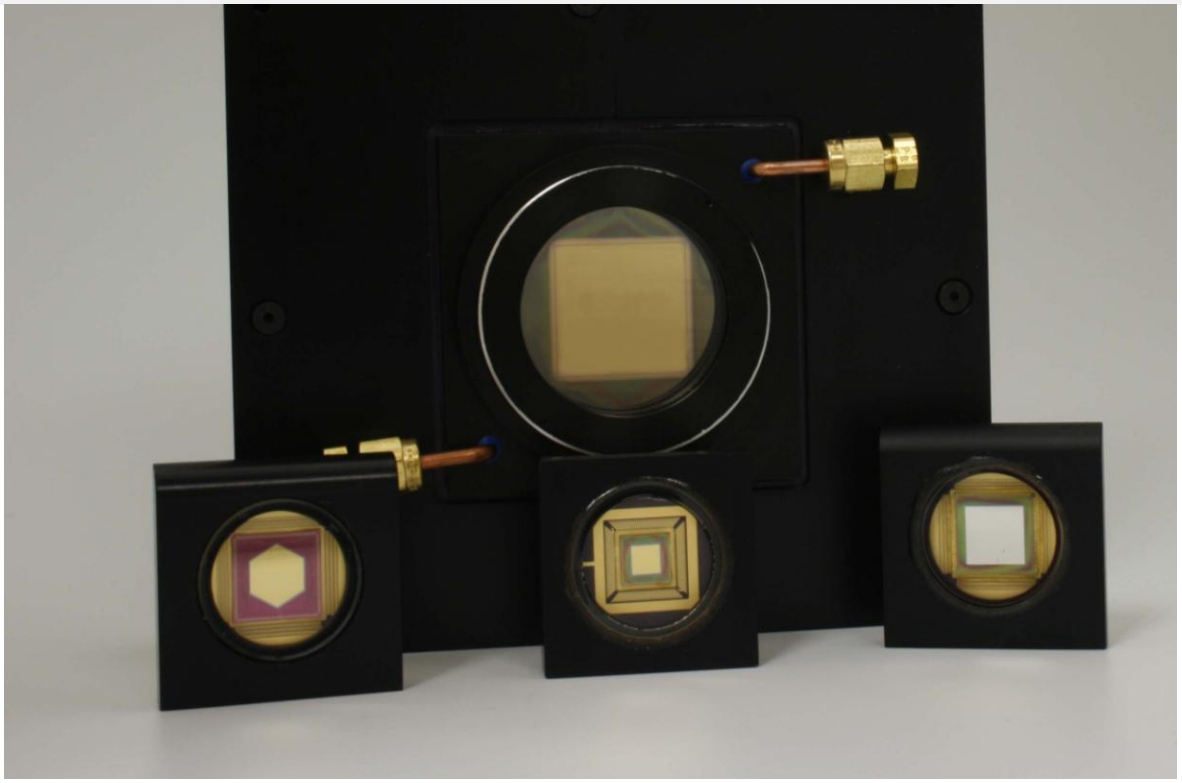
MEMS DM:
Etch away sacrificial materials, CPD, and apply reflective coating



Electrical Interconnects:
Die Attach and wirebond to custom ceramic chip carrier

(courtesy Boston Micromachines)

Electro-static Micro-Electro-Mechanical Systems



Square DM arrays

140, 1024, 4092 actuators

0.3 to 0.45 mm pitch

1.5 to 5.5 μm stroke (pitch dependant)

<< 1 ms response time

Hexagonal tip-tilt-piston DM arrays

331 segments (1021 in development)

0.6 mm pitch

2 μm / 6 mrad stroke

<< 1 ms response time

(courtesy Boston Micromachines)

Pros/Cons of MEMS DMs

- Cons
  - Sub mm pitch: not suitable for ELTs
  - Few microns stroke
  - Optical window in front of the DM
  - Some yield issues (dead actuator)
  - Field operability to be demonstrated (lifetime TBC)
- Pros
  - Very large number of actuators (scalability)
  - Good accuracy and long term stability (no creep effect)
  - Reliability
  - Short response time
  - Reasonable recurrent cost (expensive R&D though)

Preliminary assessment of DM technos we experience so far

	8m class telescope			40m class telescope			
	SCAO	MCAO	XAO	SCAO	MCAO	LTAO & MOAO	XAO
number of actuators	200-400	200-400	1200	5 - 6000	2.5-3500 iv)	1-4000	<30000
pitch (mm)	30[i)] / -[ii)]	-[ii)]	- [ii)]	30[i)] / 1.5 to 5	6 to 8	1-2	1-2
mechanical stroke (mm)	10	6 to 10	2 or 10	40 to 80 **2-3 (tweeter)**	5-10	5-6 **Open loop**	2 to 3
control bandwidth[iii)] (Hz)	40-80	40-80	110	40-80	40- 80	20-30	110
Stacked array DM	✓	✓	😐	😐	😐	☠	☹
Bimorph DM	✓	😐	☠	☠	☠	☠	☠
Large Voice coil actuator DM	✓	☠	☠	😐	☠	☠	☠
Small Voice coil actuator DM	✓	😐		☹	☠	☹	☠
MEMS	✓	😐	✓	☠	☠	☠	☹

Conclusions

- Significant R&D efforts are still required in DM technologies to meet the expectations of AO at the Extremely Large telescopes
- Different DM solutions are needed for different AO types from very large DM, medium size and mini DMs
- DM designs & solutions should also addressed the control electronics, connecting and cabling
  - More efficient, more compact electronics,
  - Low voltage or low current, low heat dissipations?➔ ASIC???
  - Ideally integrated or piggy back on the DM?
  - More compact cable bundles, connectors