Electromagnetic DM and control technology at TNO

for future Adaptive Optics

Teun van den Dool, Niek Doelman

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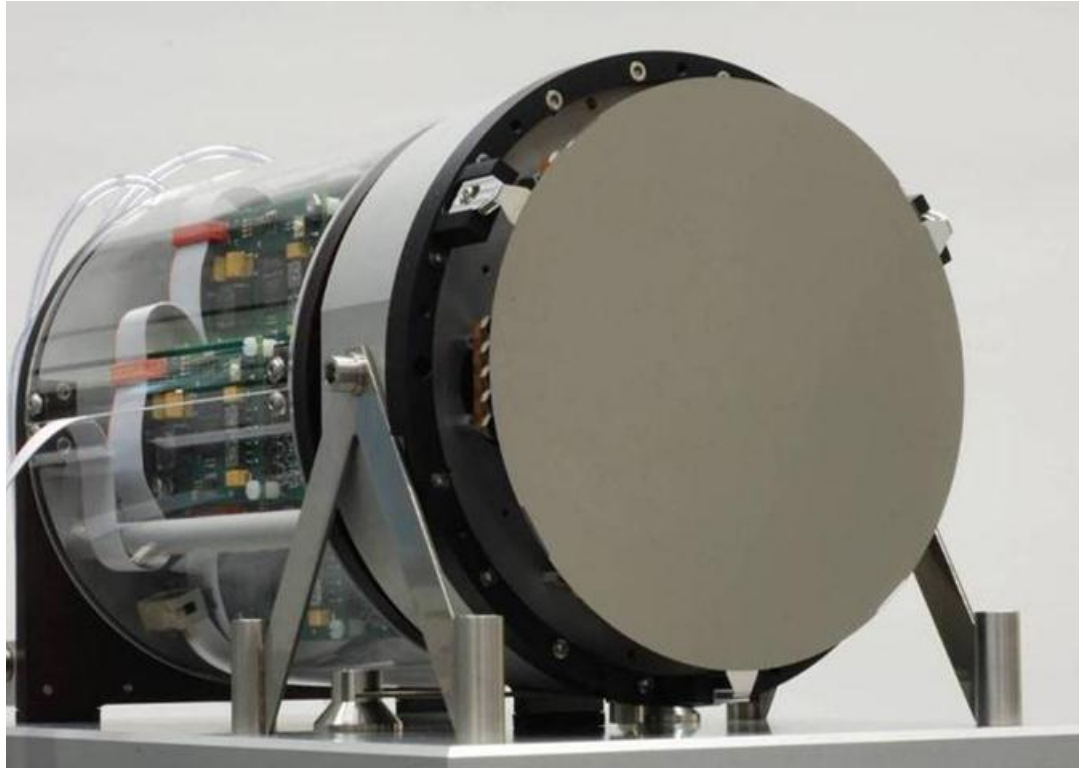


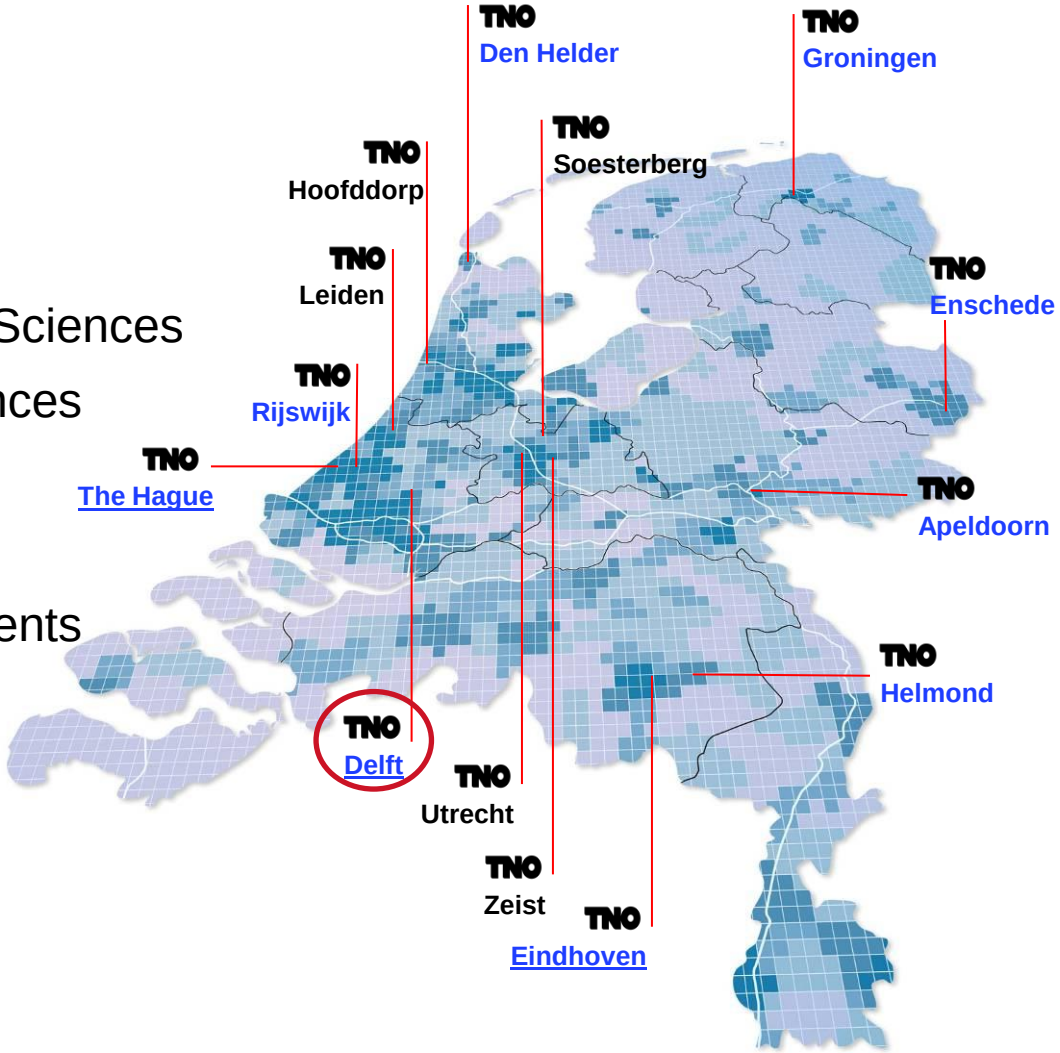
TNO in The Netherlands

Three Areas of Expertise:

- Technical Sciences
- Earth, Environmental and Life Sciences
- Behavioural and Societal Sciences

Technical Sciences (a.o.):

- Earth based telescope instruments
- Space instruments
- Semiconductor industry
- Medical

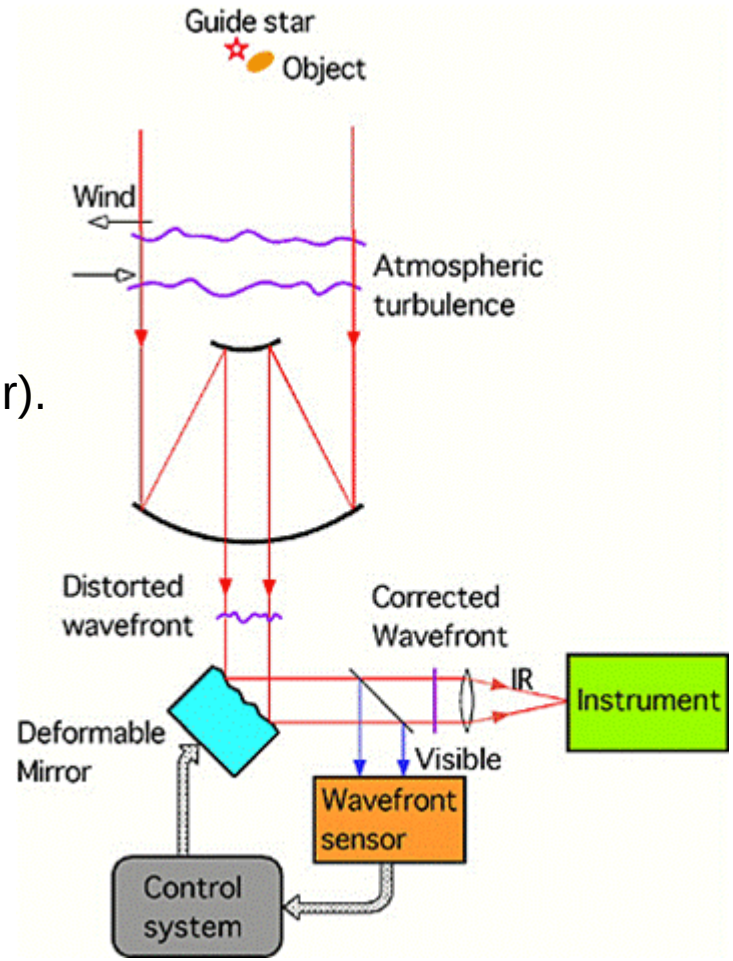


TNO innovation for life

TNO DM application target:
AO for spatial and temporal wavefront correction

Example applications at TNO:

- Atmospheric turbulence effects in telescopes and (optical) point-to-point communication.
- Ophthalmology / OCT (vitreous humour).
- Laser cavities.
- Optical recording.
- Lithography.



AO/DM requirements (on which 1st presented design is based)

- Case: VLT 8m telescope.
- Improvement to diffraction limit (at 550 nm).

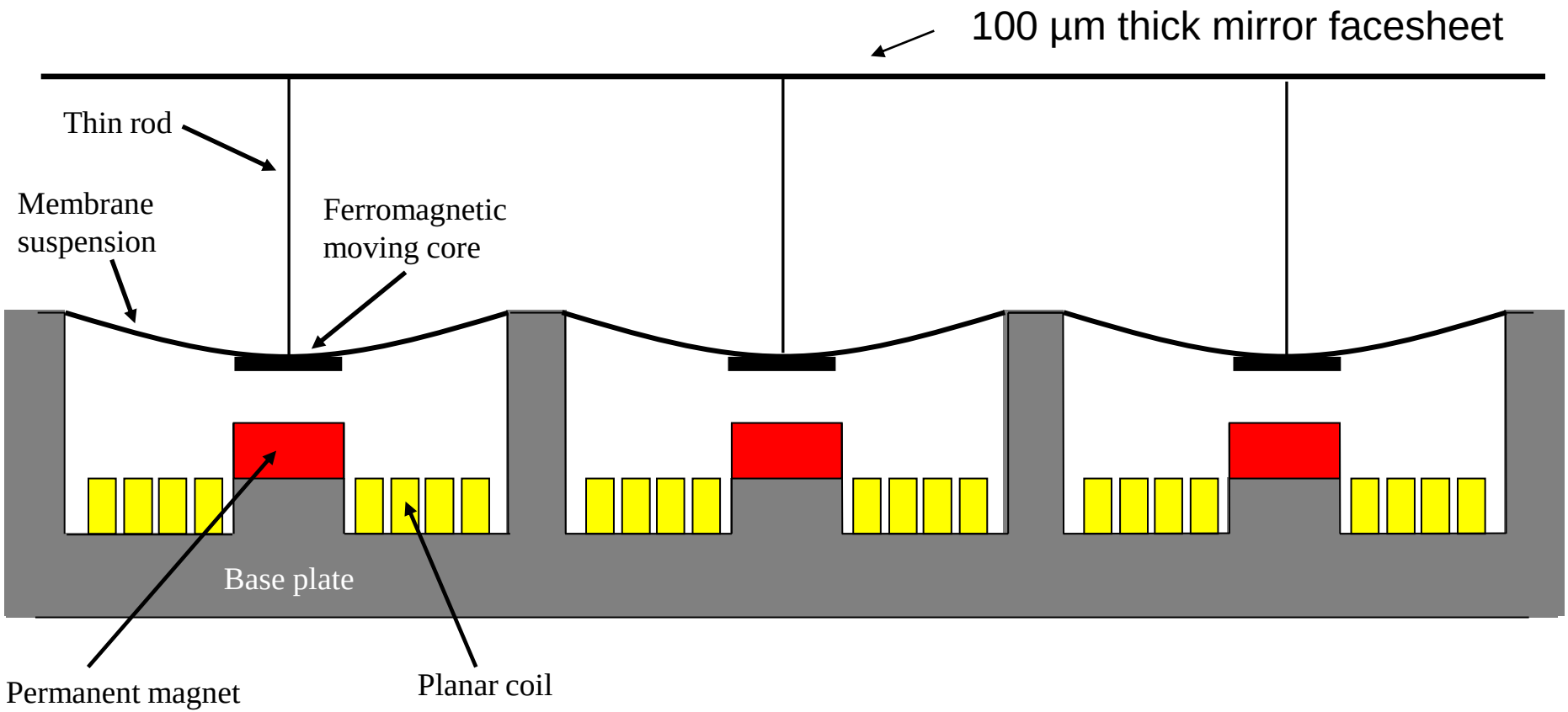
- Driving parameters:
  - The fitting error, caused by a limited number of actuators.
  - The temporal error, caused by a limited control bandwidth.

- Derived requirements:
  - # actuators: >5000 (pitch: 6 mm, 500 mm mirror)
  - Total stroke: > +/-10 um
  - Inter-actuator stroke: > +/-0.4 um
  - Resolution: < 5 nm
  - Control band-width: > 200 Hz (=> first resonance frequency >~1000 Hz)
  - Power dissipation: mirror temperature increase: < 1 K

Design principles of TNO's DM

- Optical face sheet: Continuous, flat membrane mirror
- Actuation principle: Electro-magnetic
- Dynamic behaviour: Linear (no hysteresis enables open loop operation)
- Scalability: Modular design (mechanical, electrical, control)
- Power dissipation: Low; no active cooling needed
- Driving electronics: Low voltage, low latency
- Components: Low cost, straightforward manufacturing

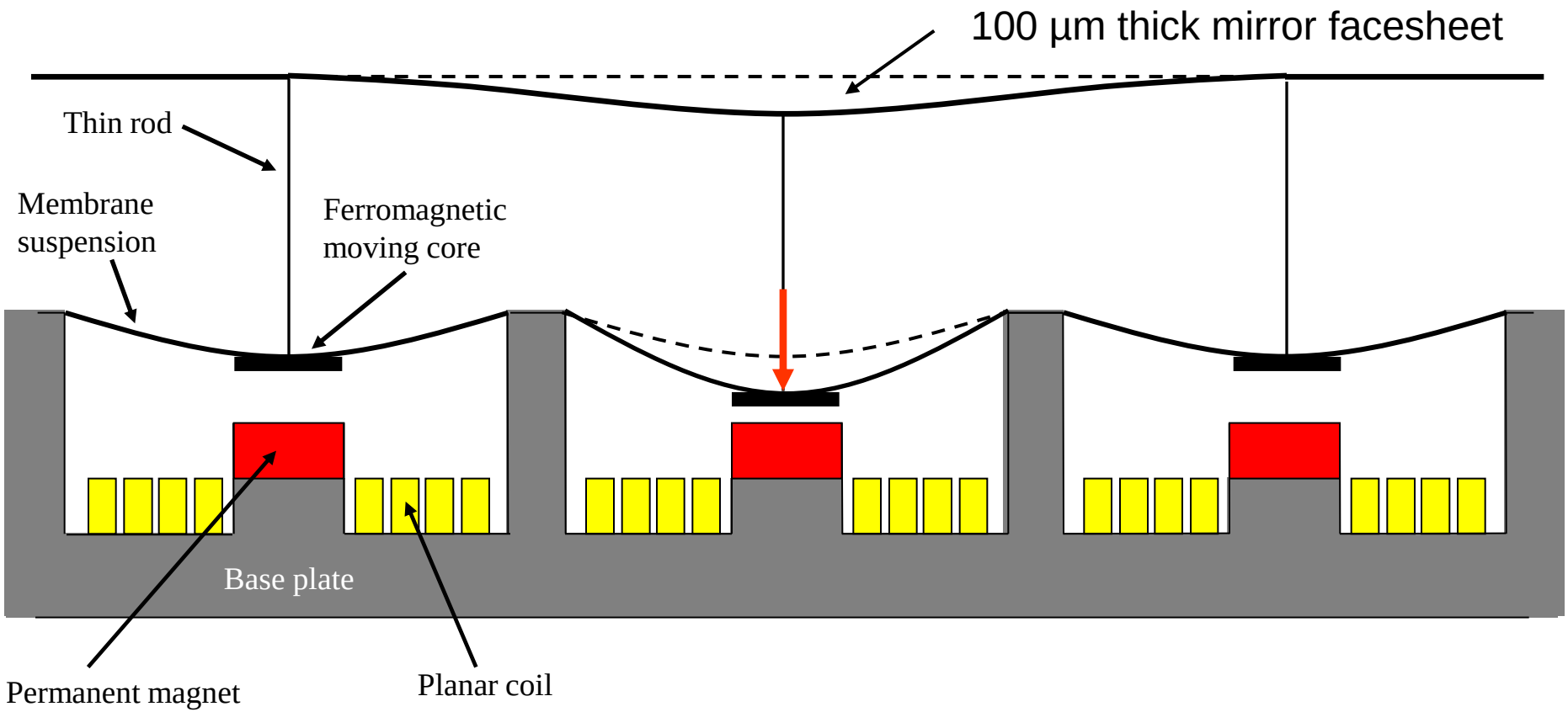
Concept of TNO's DM: variable reluctance actuator



Electromagnetic force **Electromagnetic force** **Electromagnetic force**

PM **PM** **PM**

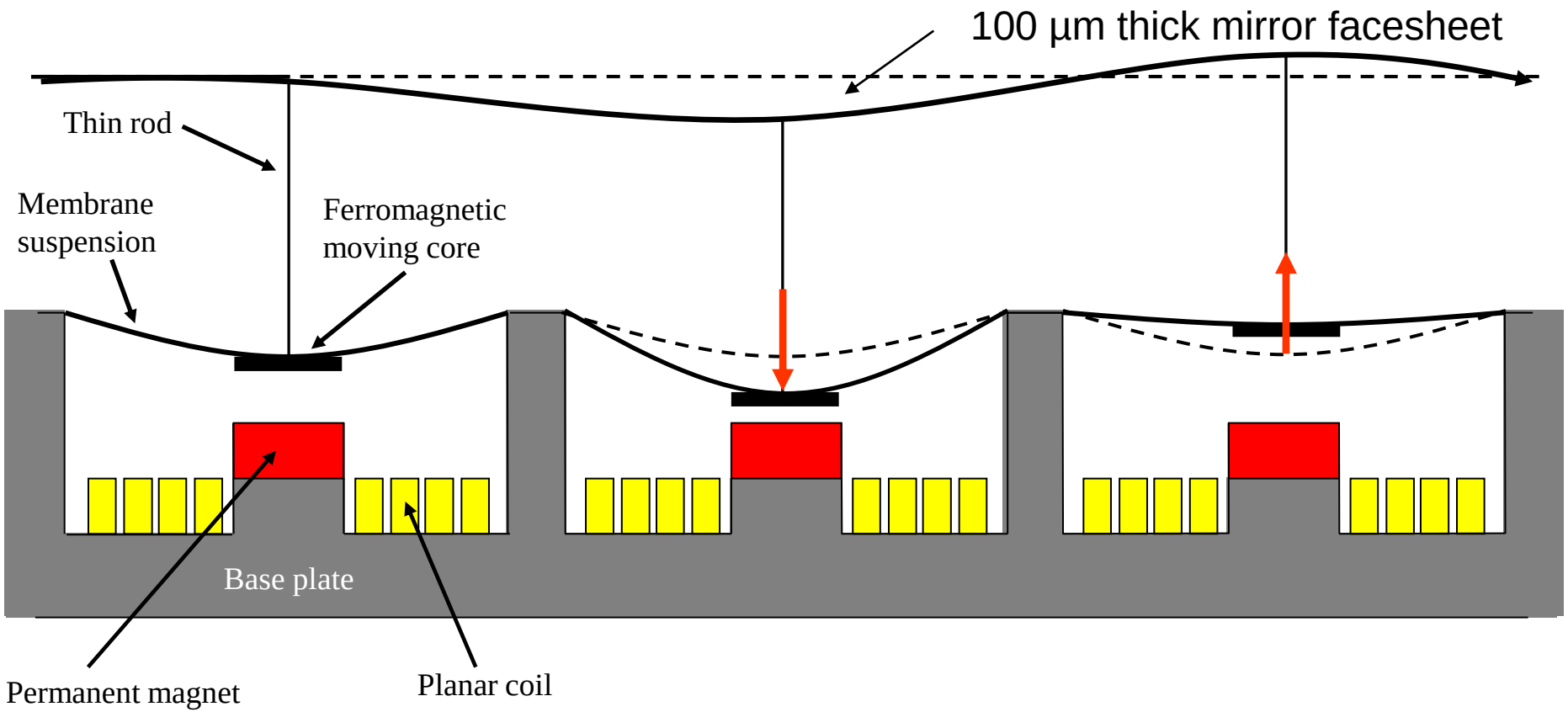
Concept of TNO's DM: variable reluctance actuator



Electromagnetic force **Electromagnetic force** **Electromagnetic force**

PM **PM + Coil** **PM**

Concept of TNO's DM: variable reluctance actuator



Electromagnetic force

PM

Electromagnetic force

PM + Coil

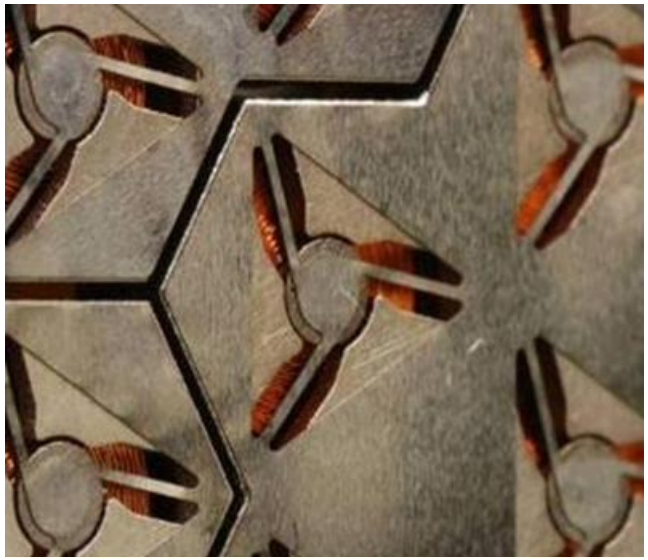
Electromagnetic force

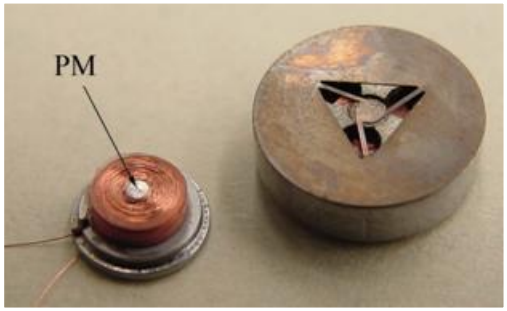
PM - Coil

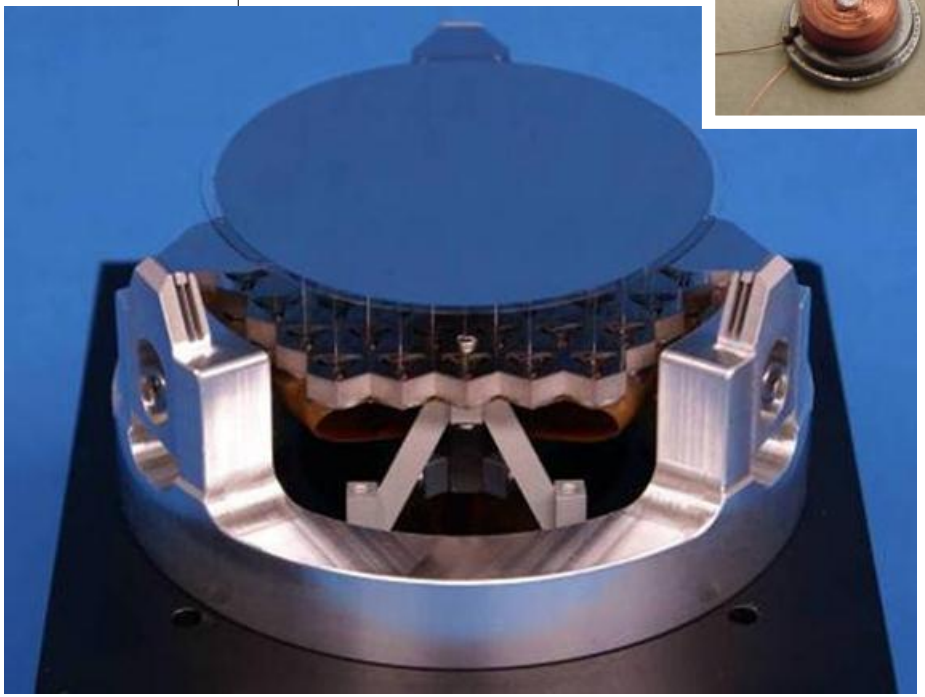
Modular design

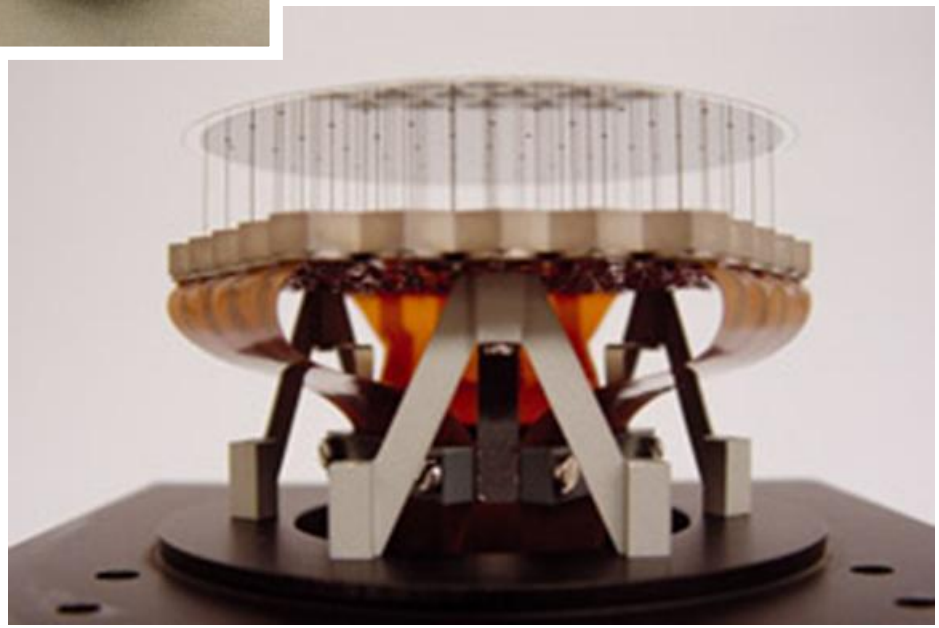
- 1 module has 61 actuators.
- Pitch = 6 mm (scalable 3-30 mm).

Ø50 mm prototype.



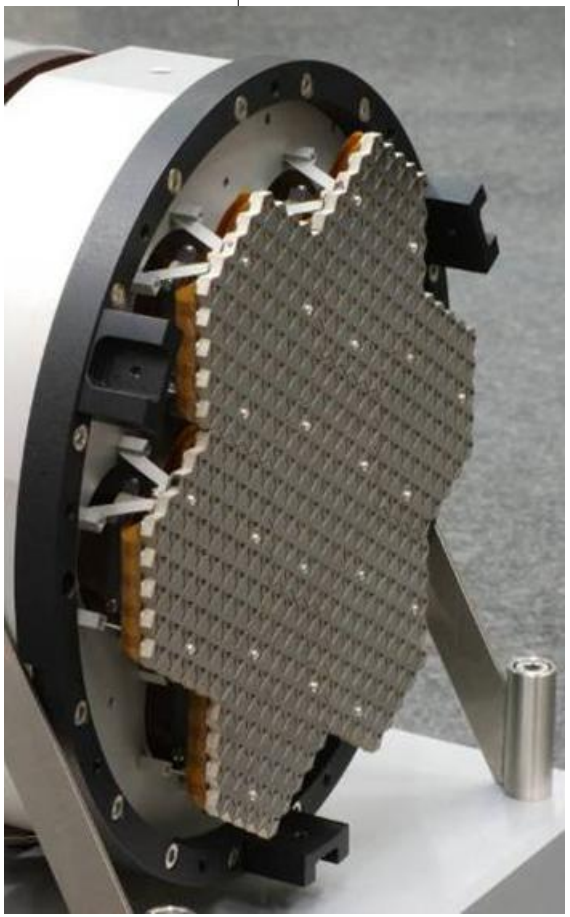


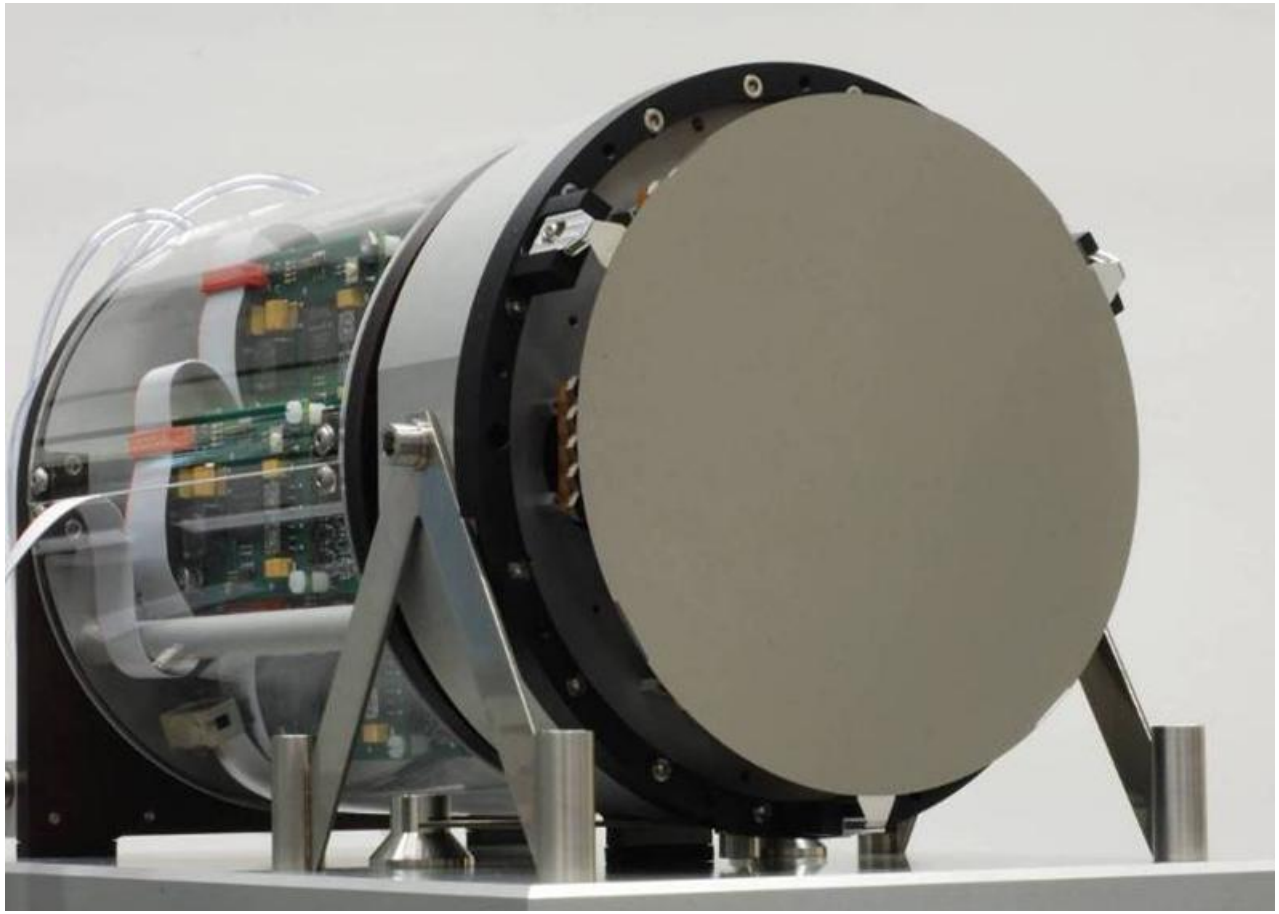




Ø150mm version with 7 modules, 427 actuators

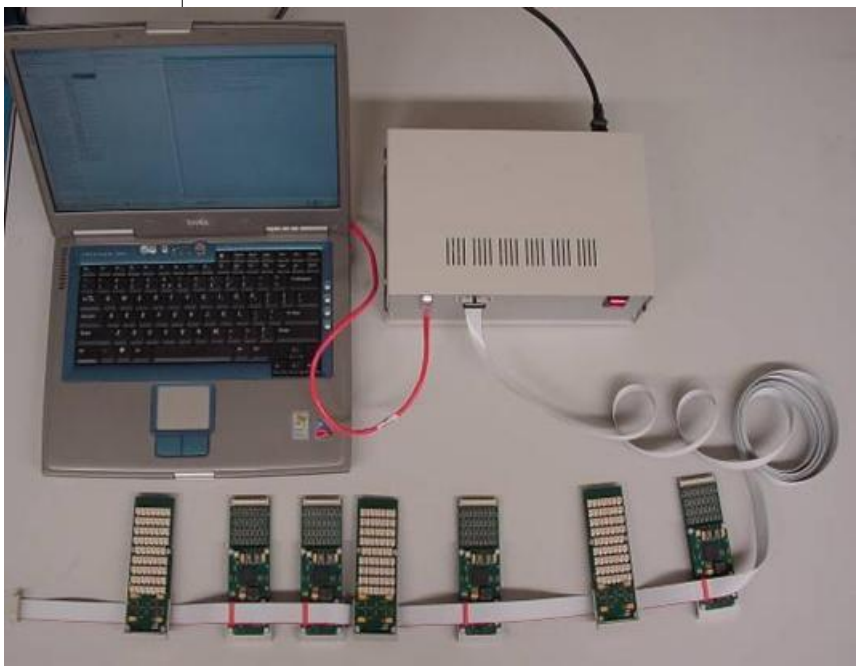
With integrated face-sheet (Pyrex) and electronics

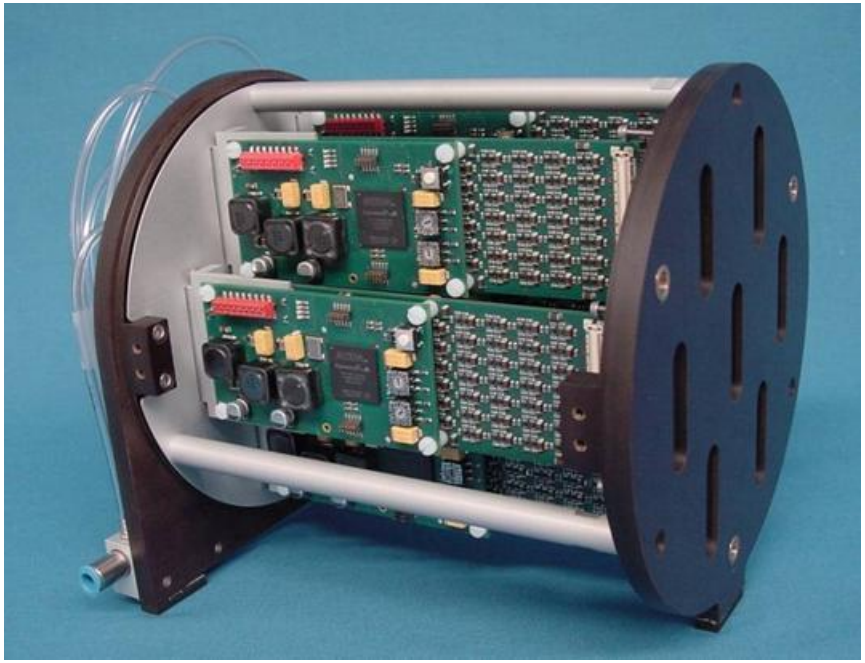




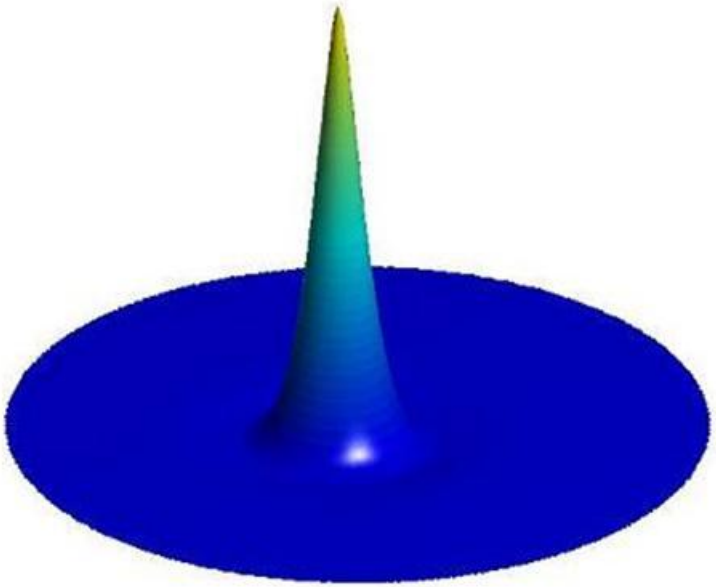
Modular electronics

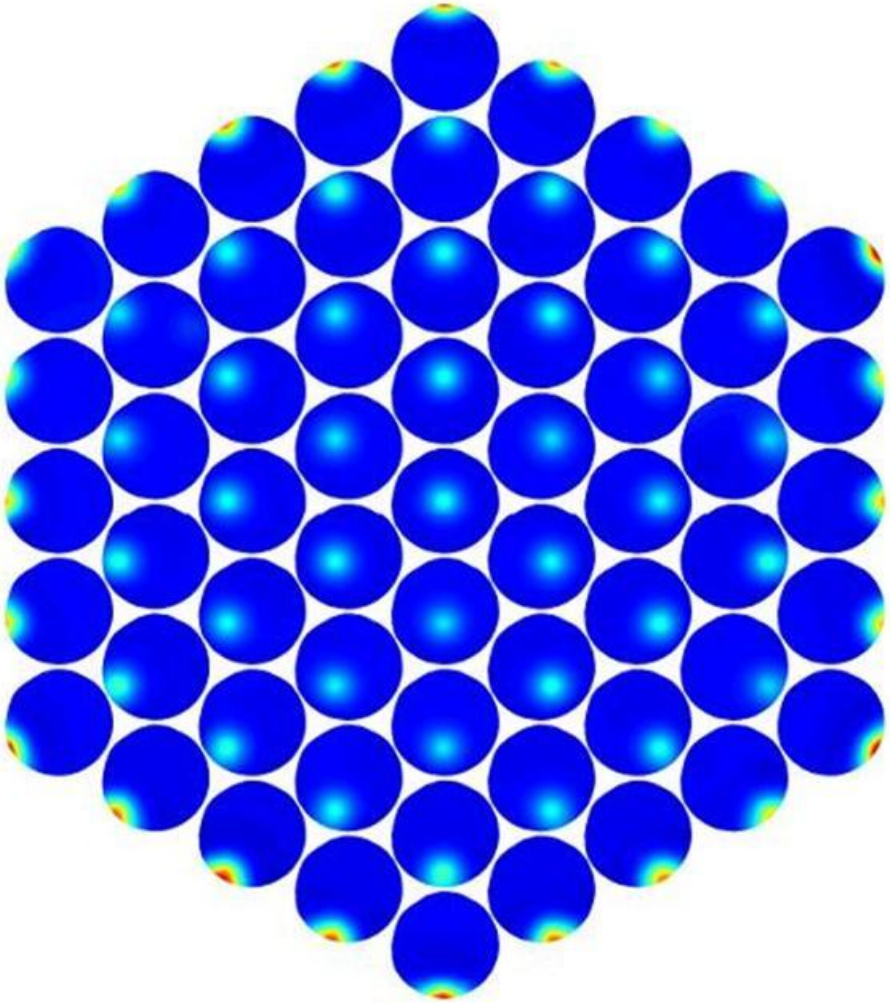
- Each module of 61 actuators is driven by a single PCB.
- 16 bit digital drive signal.
- Low power consumption (multi-drop LVDS – ethernet connection).
- Up to 32 PCB's on 1 multi-drop cable.
- Full duplex line operates at 40 Mbit/s.





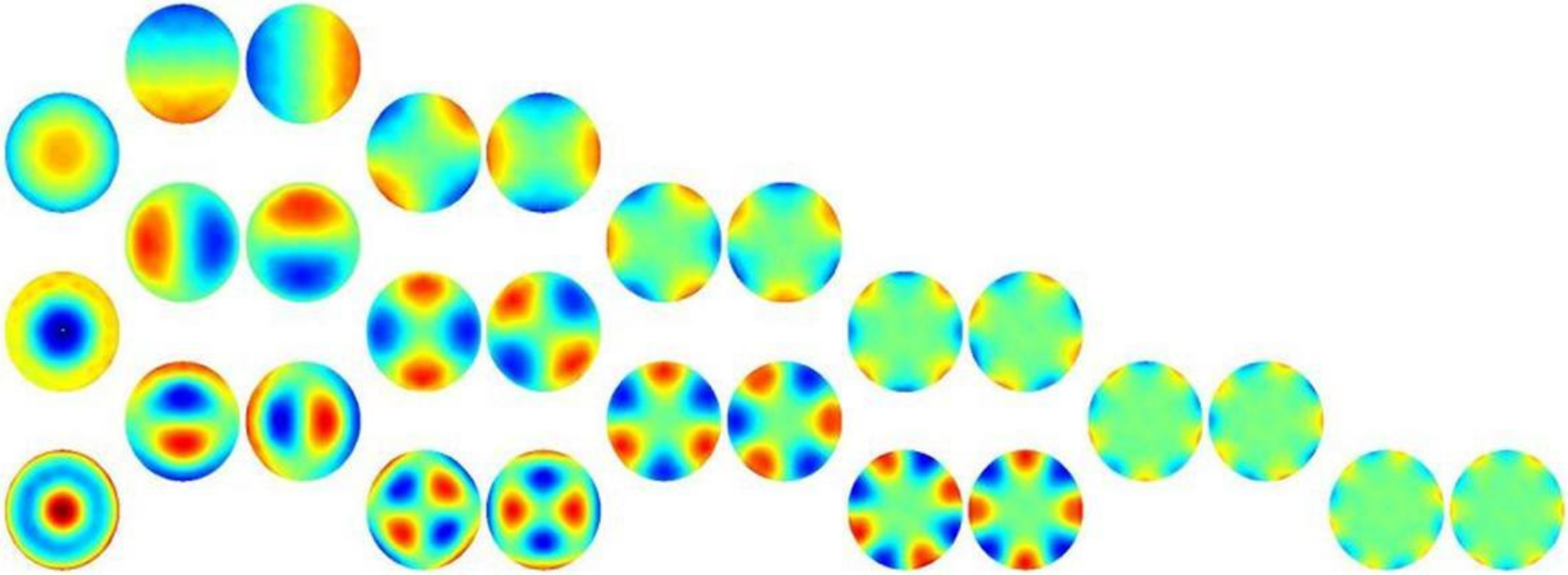
Influence functions



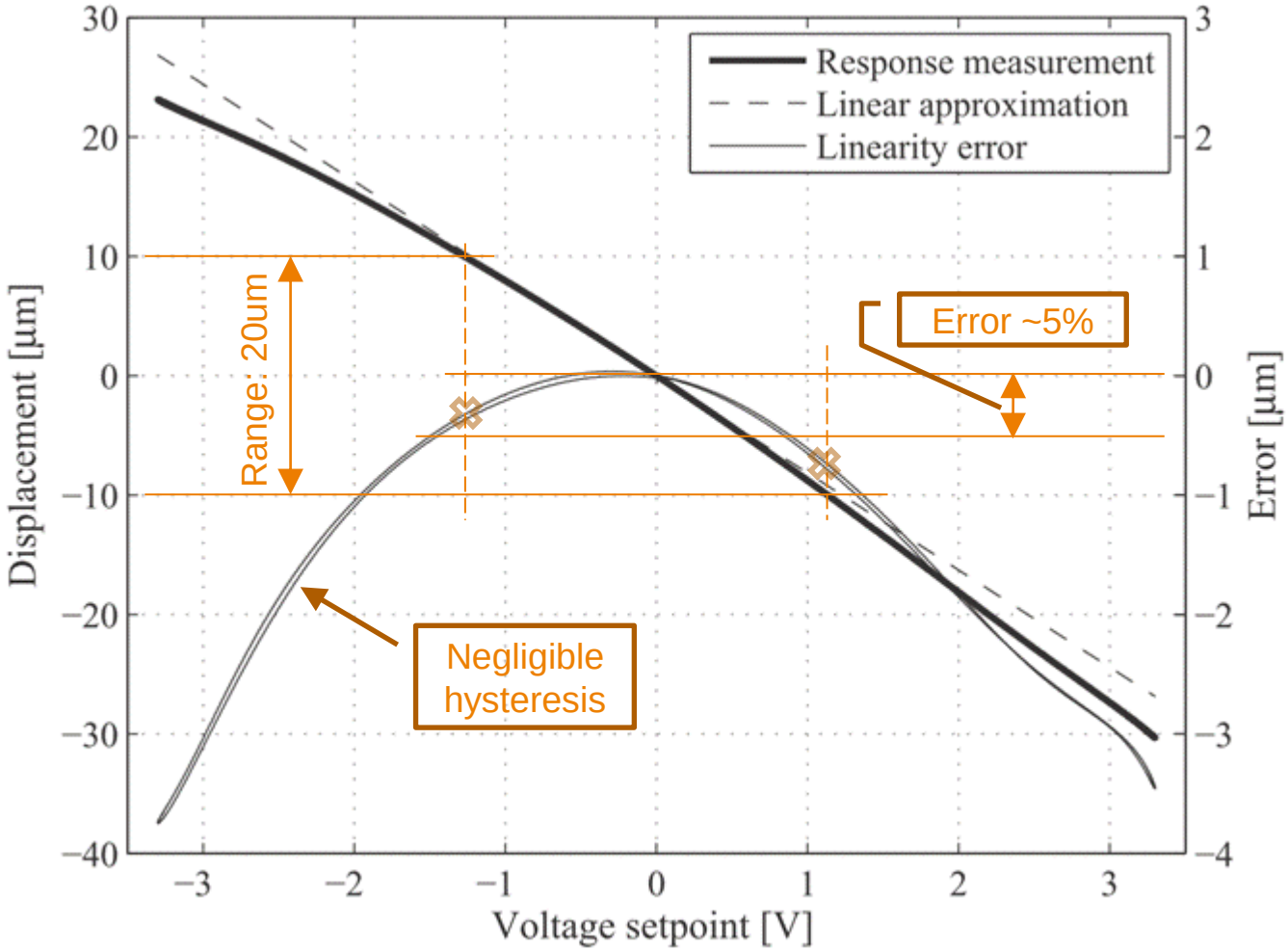


Measured Zernike modes (1 module, Ø50mm, 61 actuators)

~ 25 nm deviation (RMS) from perfect Zernike shape



Linearity & Hysteresis



Specifications of TNO's baseline DM

(currently 6 mm pitch version)

Maximum actuator stroke	20 µm (peak to valley)
Inter-actuator stroke	> 1 µm (peak to valley)
Actuator spacing	6 mm (scalable 3 .. 30 mm)
First resonance frequency	> 700 Hz
Settling time	~1 ms (mainly electronics, <0.1ms mech.)
Power dissipation per channel	~ 10 - 20 mW (mainly electronics)
Number of actuators	61..427..1159..2257..3721..5551 (scalable)
Clear aperture diameter	50..150..250..350..450..550mm (6mm pitch)
High order wavefront error	~ 25 nm (RMS)
Dynamic response	linear (no hysteresis, drift, or ageing)

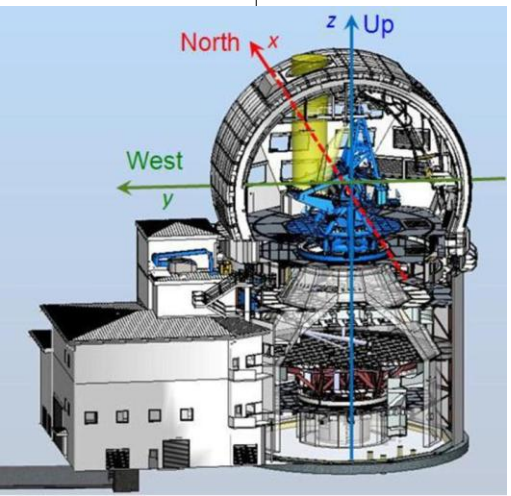
- Other:
  - Low stiffness actuation so single failing actuator has a small impact.
  - Smooth face-sheet, no introduction of higher orders.
  - Face-sheet replacement is possible.
  - Forced cooling is possible.
  - Temperature range: -10 .. +30 C

Specific applications

1. Solar telescope: handling of thermal load
2. Infrared (K-band) operation: cryogenic conditions
3. Improved actuator efficiency

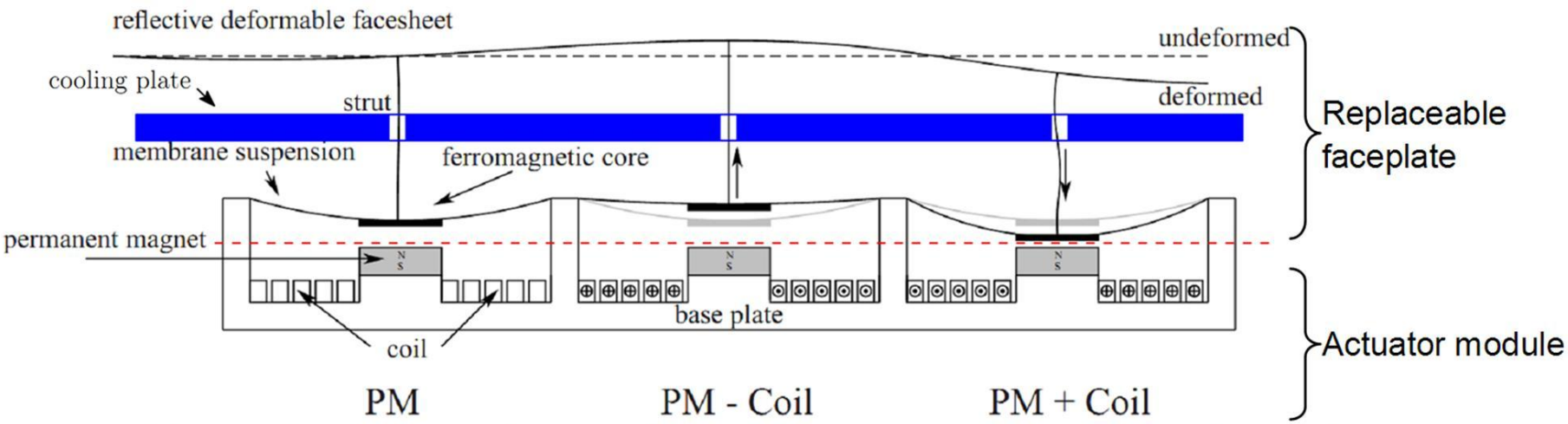
Application: ATST
(Advanced Technology Solar Telescope, Haleakalā, Hawai)

Requirements comparison	VLT	ATST
Recoatable / replaceabe face-sheet	none	required
Cooled face-sheet	none	required
DM delay (from cmd to 1% settling	~ 1 ms	< 0.2 ms
Actuator pitch	6 mm	4 mm
Actuator stroke	+/-10 um	+/-6 um
Inter-actuator stroke	0.5 um	> 2 um
Inter-actuator coupling	52 %	20 %
Number of actuators	~5000	~2000
Flatness of face-sheet (rms)	~25 nm	< 16 nm
Update rate	1 kHz	5 kHz
Driving electronics	local	remote



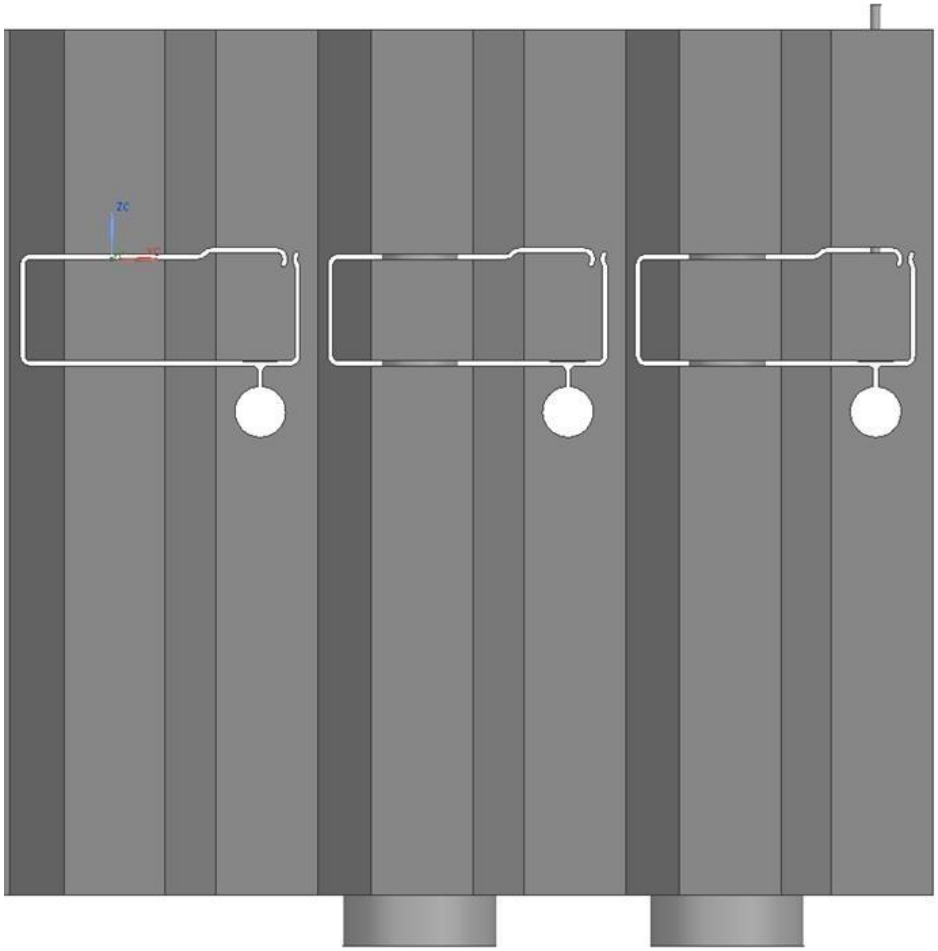
Cooling & face-sheet replacement (in “VLT” design)

Inter-actuator stroke and coupling not according to requirements.

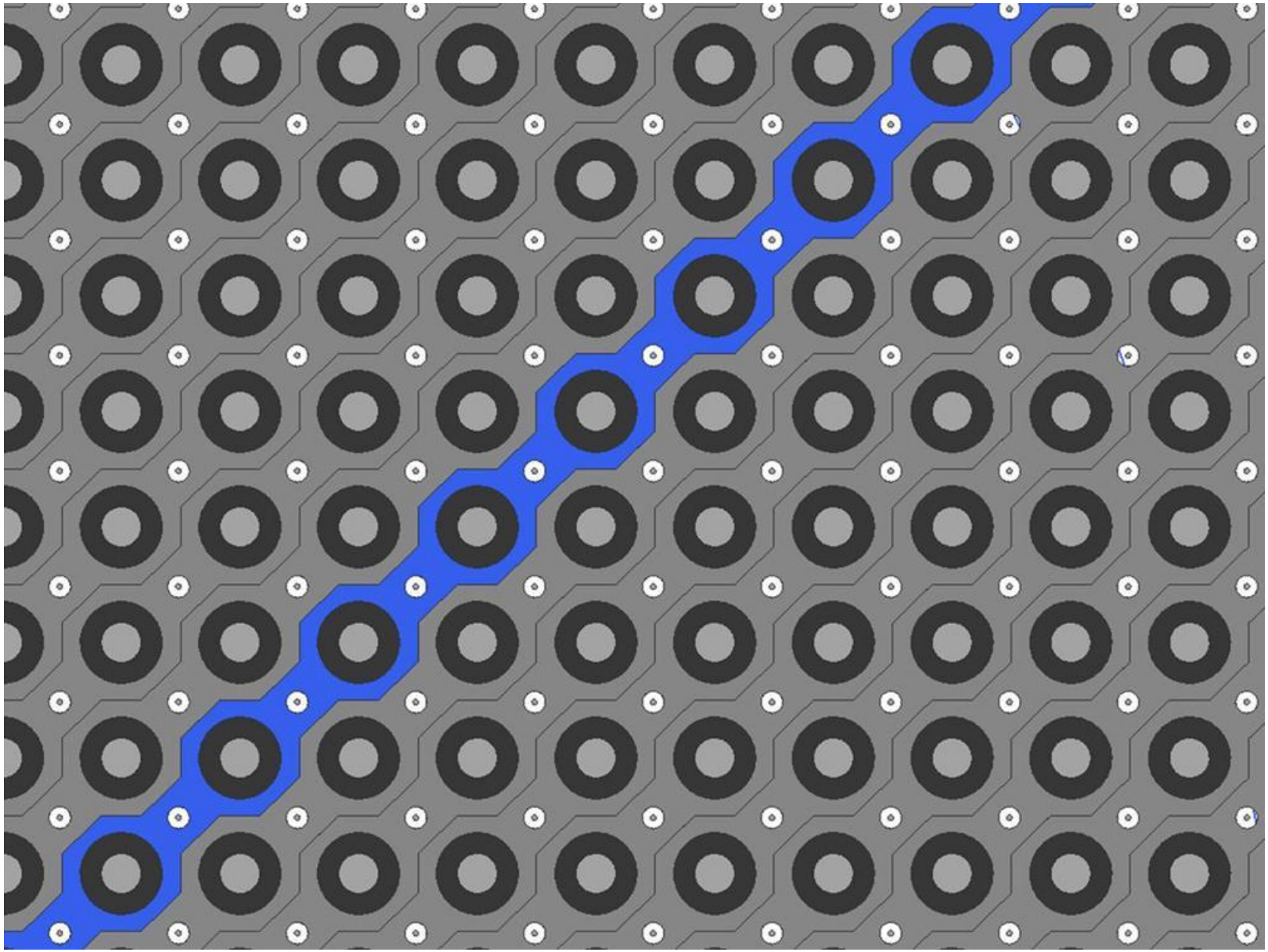


Design for ATST

- Lever for higher stiffness and higher force at the face-sheet.
- ‘Higher’ design to allow for same actuator volume at smaller pitch.
- Reluctance type actuator with large stroke and big coil.
- Modular / stackable design.



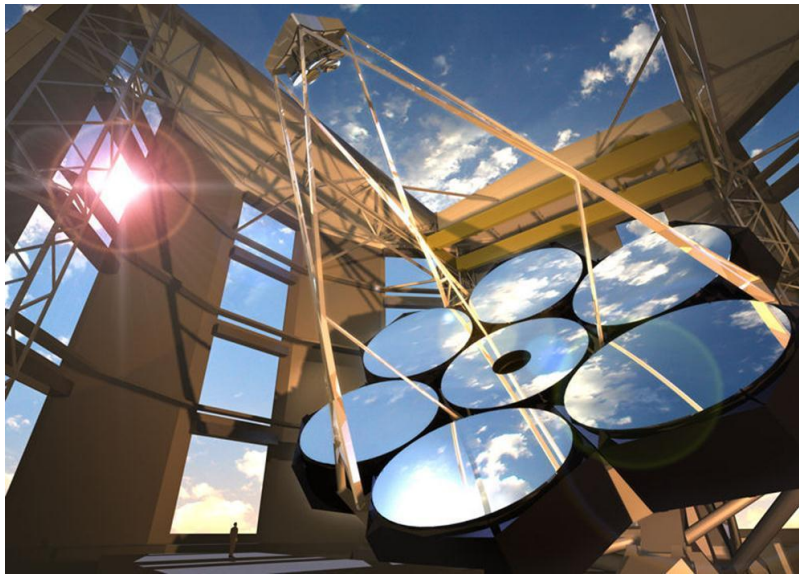
Design for ATST



Application: GMT-LTAO (Laser Tomography Adaptive Optics)

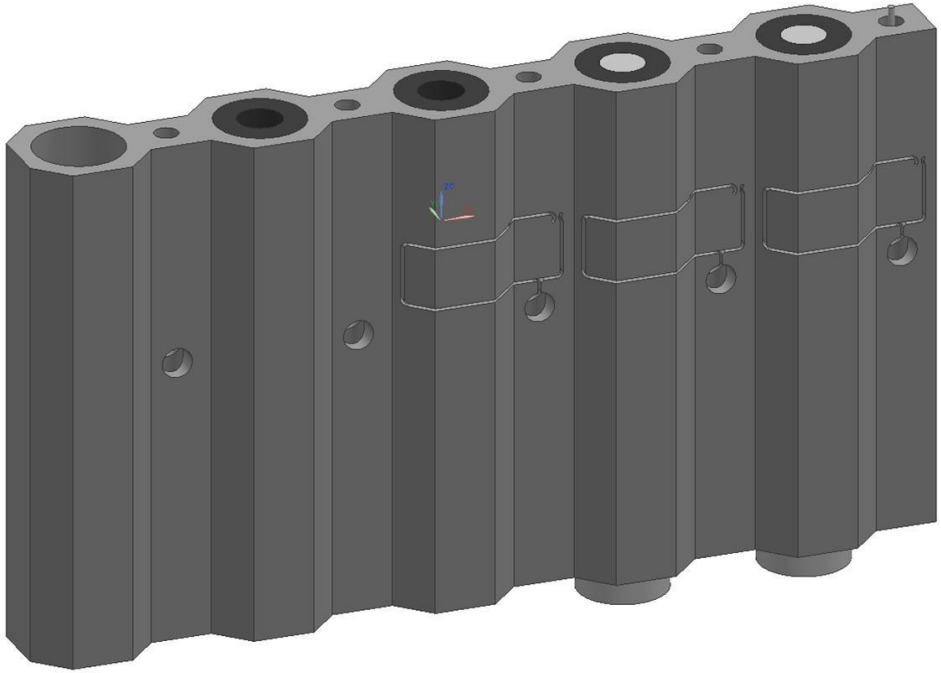
By the ANU (Australian National University)

- Infrared (K-band, 2.0-2.4 um) operation: cryogenic-vacuum DM (70K)
- Open loop steering of the DM
- Gravity in any direction
- Optical flatness: < 44 nm
- DM diameter: < 150 mm (20 – 100 mm preferred)
- > 1000 actuators => < ~4 mm pitch
- Actuator stroke: +/-2 um
- Inter-actuator stroke: > 1 um
- Actuator coupling: < 20 %
- DM band-width: 500 Hz.
- Resonant frequencies: > 5000 Hz
- Power dissipation: < 50 W



Feasibility GMT-LTAO with TNO's DM

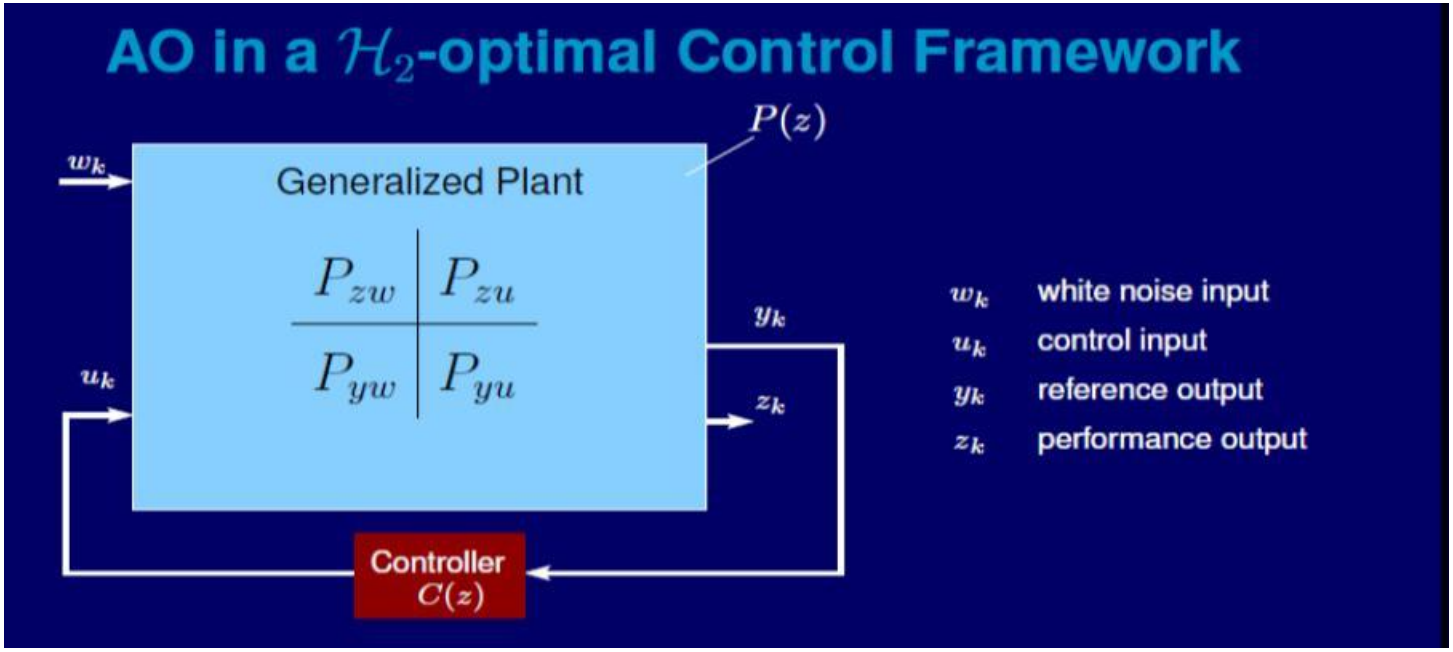
- All within specification of TNO's original design apart from actuator coupling (20% needed, 52% realized).
- Modified design for ATST also meets actuator coupling of 20%



Control for AO systems

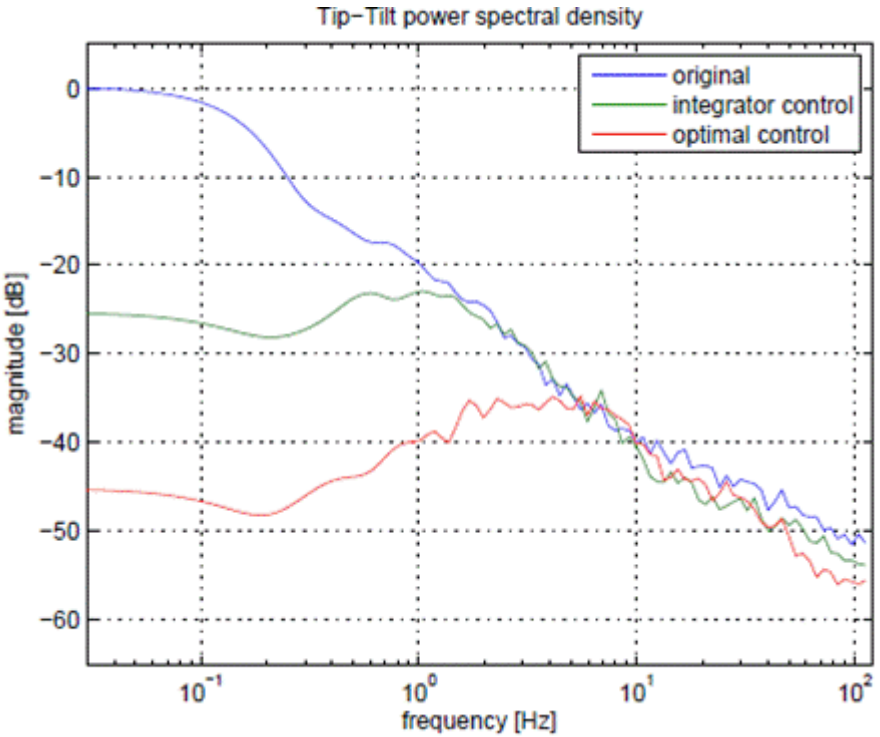
LQG-type or predictive control

- Exploit spatial and temporal correlation in the wavefront sensor data.
- Controller design is driven by wavefront sensor data (not by physical models).
- Implementation is real-time efficient.
- ref: K. Hinnen, JOSA A 24, 2007.



On-sky control validation on real telescope

- Test on 1.5m McMath-Pierce Solar telescope (Arizona, USA, Nov 2010).
- Optimal (LQG / predictive) control of tip-tilt modes.
- 10 dB improvement on image stabilization, close to prediction/theory.
- ref: Doelman, AO4ELT2, 2011.



Turbulence properties are time-variant

Therefore, optimal controller is also time-variant

1. Adaptive control to track the time-variant properties of distortions.
2. Robust control for a range of atmospheric conditions.

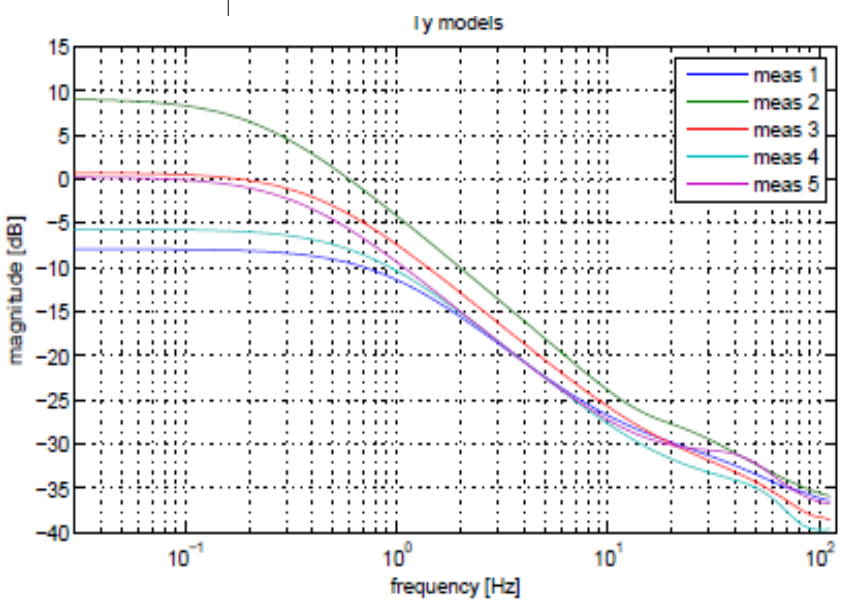
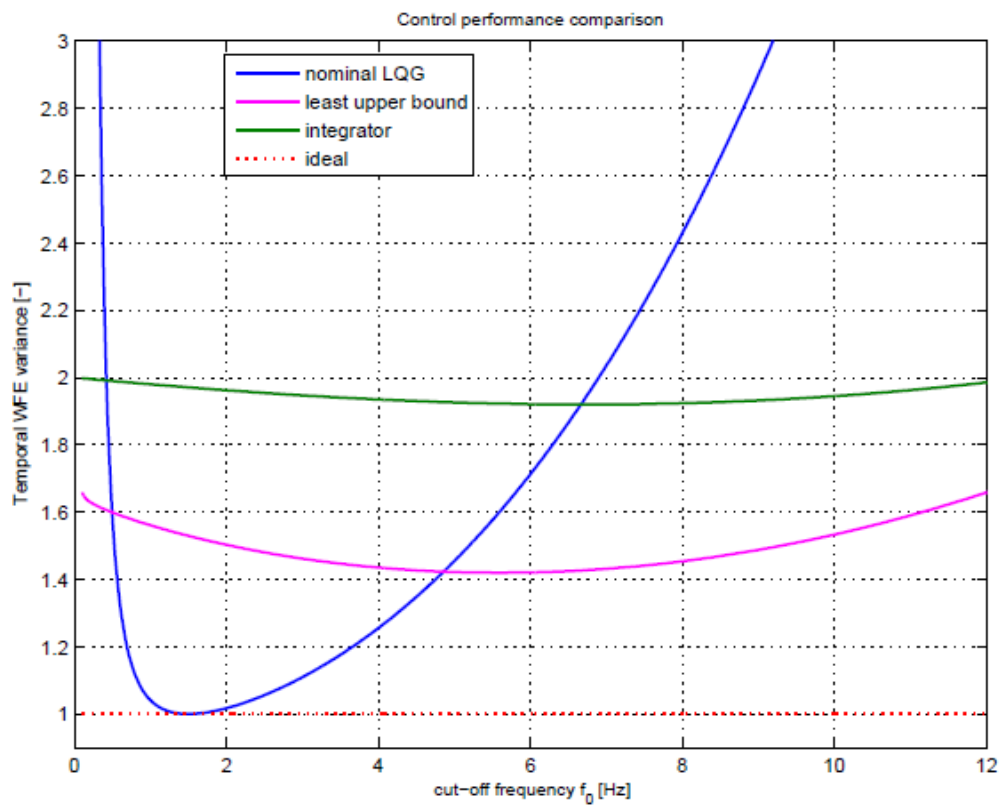
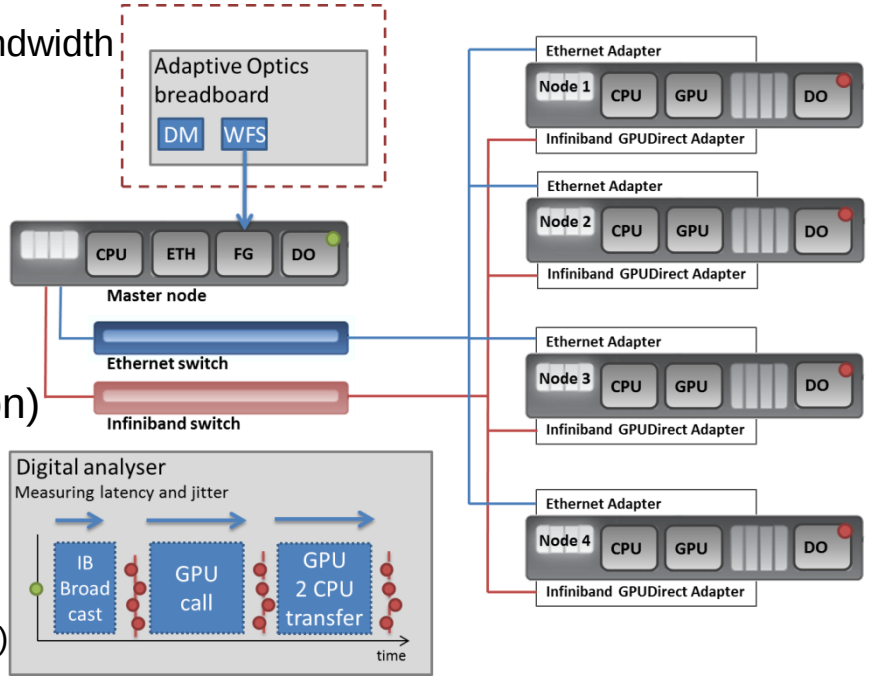


Fig. 9. Frequency responses of disturbance models for T_y.



Real-time control architecture for large AO systems

- Study for the E-ELT instrument EPICS (Exo-Planet Imaging Camera and Spectrograph)
- Large and fast AO system:
  - 4.10^4 actuators in DM, 4.10^4 "sub-apertures" in WFS, 2-3 kHz frame rate
  - Matrix-Vector Multiply-add operations: ~ 6 TMAC/s, **~ 24 Tbyte/s memory access**
- GPU (instead of CPU or FPGA) cluster selected for:
  - Fast computation and high memory bandwidth
  - Flexibility
  - Limited software development time
- Experimental GPU-cluster to study real-time aspects: 4x Nvidia GTX570 + Xenomai RTL + CUDA (parallellization)
- 96% of theoretical memory bandwidth achieved (and only 4% proc.power).
- 170 GPUs needed for EPICS (30 in 2020?)

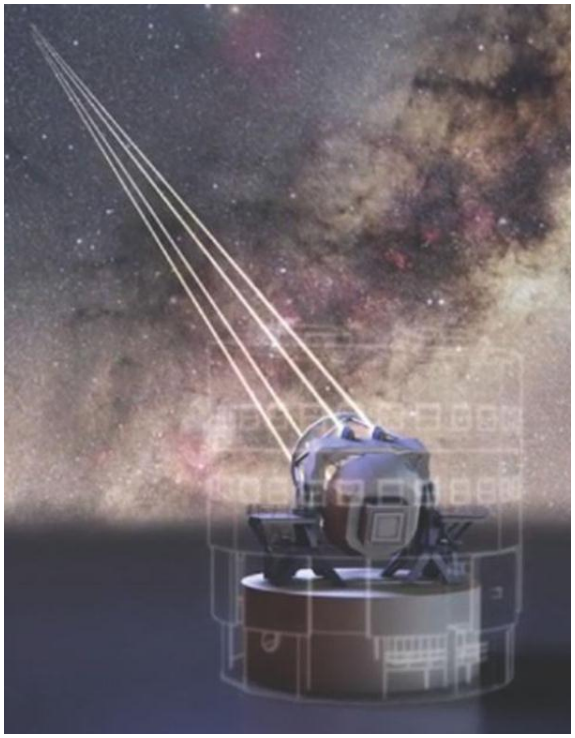


Launch Telescopes for Laser Guide Stars

(VLT 4LGSF Optical Tube Assemblies)

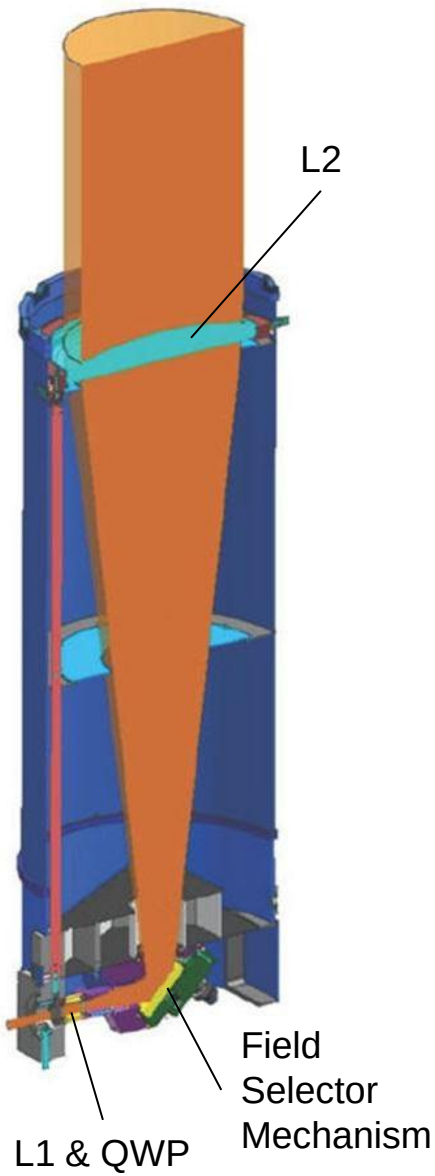
Requirements:

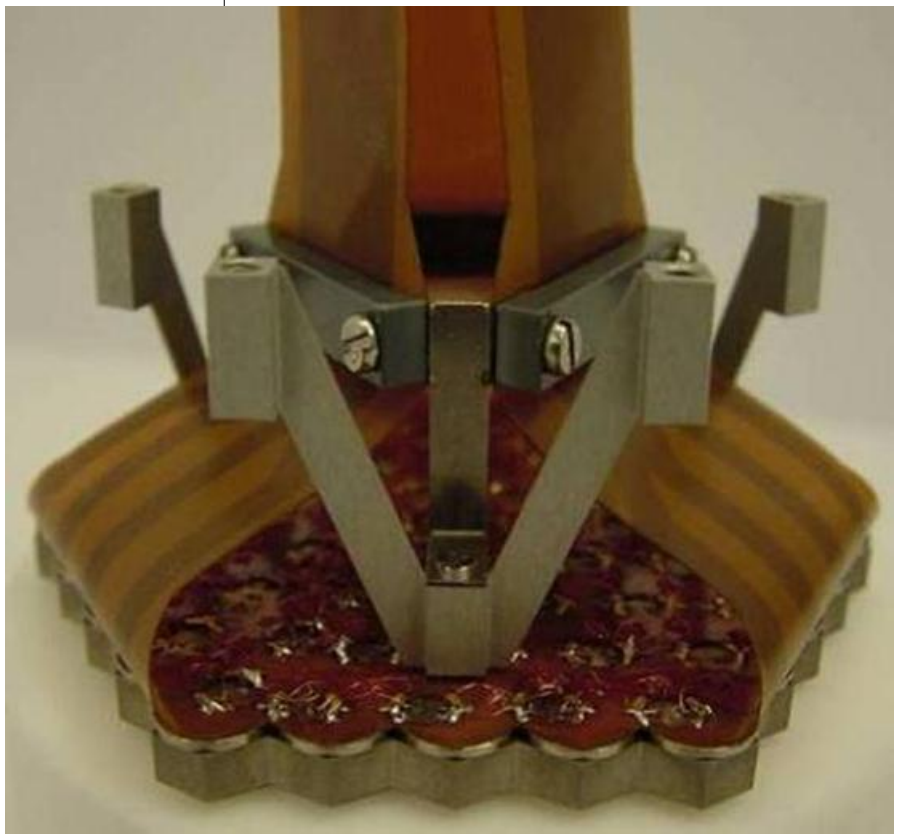
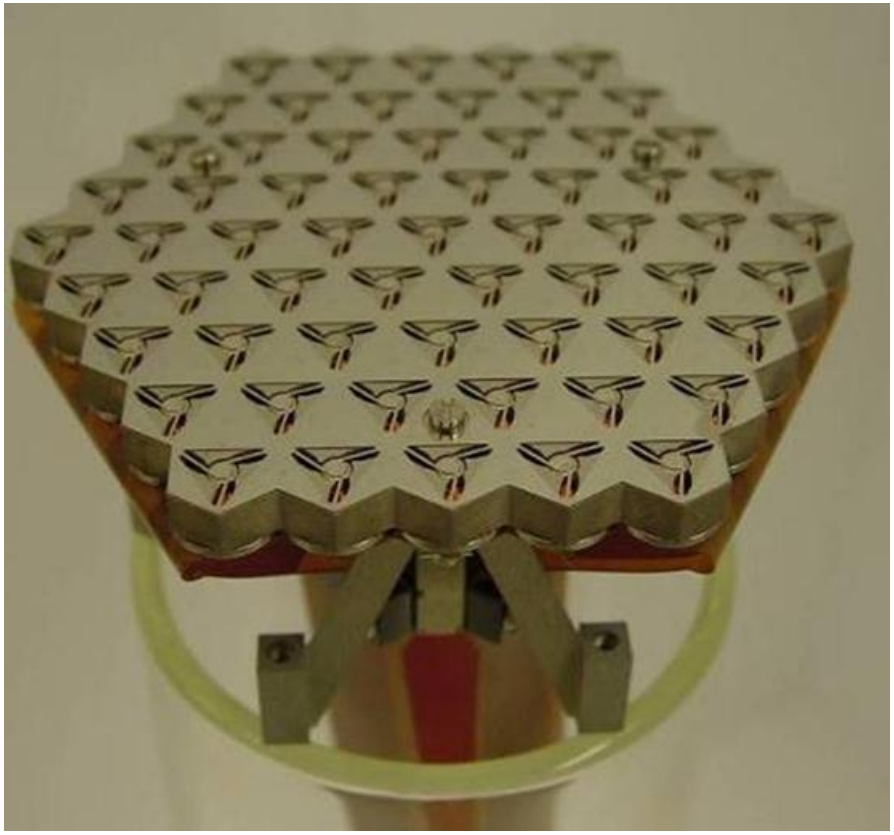
- WFE: < 50 nm (< 25 nm realized) for 0 – 15 deg.C and 0 – 60 deg tilt.
- Thermally induced defocus: < 118 nm (90 nm realized).
- On sky pointing error: < 0.3 deg (< 0.1 deg realized) over +/-4.8 deg range.
- Polarization extinction: > 97% (99.7% realized)
- Throughput: > 95% (97.7% realized).



OTA construction

- 300 mm steerable output beam
- 4.8 arcmin field of view on-sky
- 20x Galilean beam expander
- Double concave L1
- Aspherical 380 mm L2
  - 320 um departure from best-fit sphere.
  - Measured with TNO's NANOMEFOS (15 nm rms).
  - Custom 589 nm coating.
- Flat field selector mirror with mechanism:
  - +/-6.1 mrad tip & tilt range.
  - 1.5 urad rms accuracy.
  - settling time: 1 arcsec in 0.2 sec.
  - 2 self-locking spindle drives.
- Passively a-thermal



TNO

Thank you