“ Performance of a thermally deformable mirror for correction of low-order beam aberrations”

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Outline

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2. Prototype of a Thermally Deformable Mirror (TDM)
   - Principle
   - Experimental setup

3. How to perform correction of low-order aberrations
   - Calculation of the correction
   - Zernike polynomials
   - TDM properties

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Motivation

Advanced Gravitational Wave Detectors

Injection system

High power continous laser > 100 W

Thermal lensing effects in the Input Mode Cleaner and the Faraday Isolator optics

Distorsion of the laser beam fundamental mode

Potential source of noise - Power losses :

up to 10% mismatching onto the interferometer

Advanced Virgo injection laser beam

@1064 nm

2.6 mm beam radius

Estimated RoC variations: 200 m

Detection system

Thermal lensing effects

Mismatching onto the Output Mode Cleaner[1]

→ Need of optimisation of the coupling by **correction of optical aberrations due to thermal lensing in the system**

[1] " Modematching feedback control for interferometers with an output mode cleaner"

N. Smith-Lefebvre, N. Mavalvala, submitted for publication

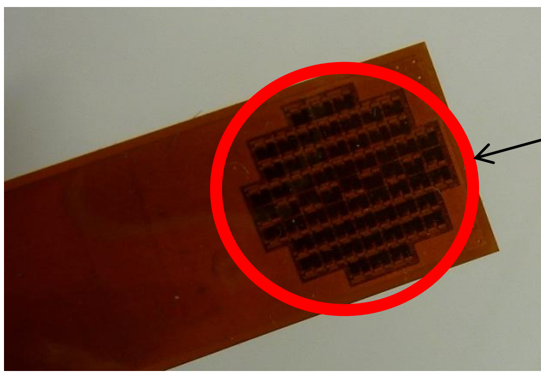
First prototype of a Thermally Deformable Mirror (TDM)

Local temperature control of the substrate

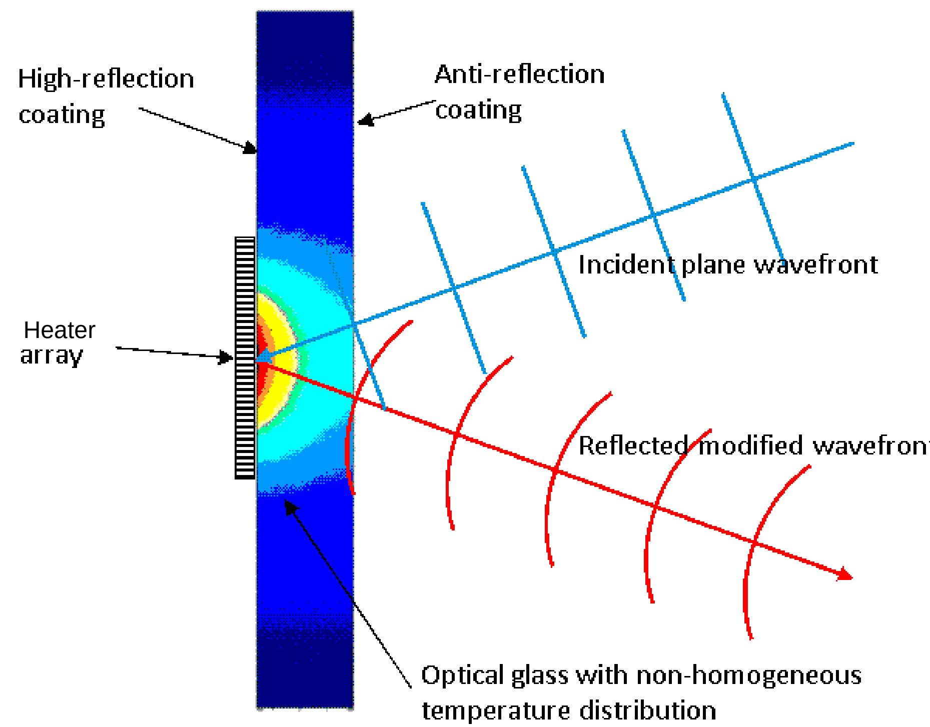
Modification of the optical path length (OPL) according to[2]:

$$OPL = \int_C \left(\Delta T(s) \left[\frac{dn}{dT} + \alpha_T (1+\nu) n \right] + n \right) ds$$

Temperature local increase — **Thermo-optic coefficient** — **Thermo-elastic coefficient**



Array of 61 independently controlled actuators



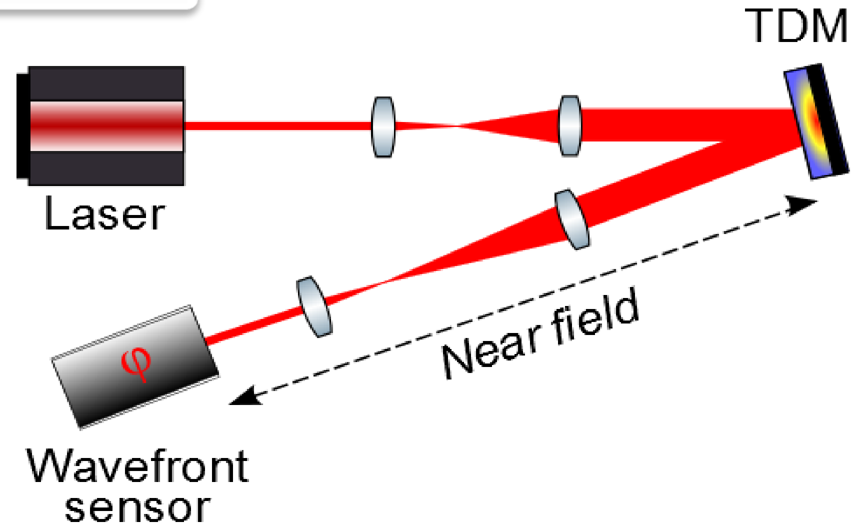
Thermally deformable mirror

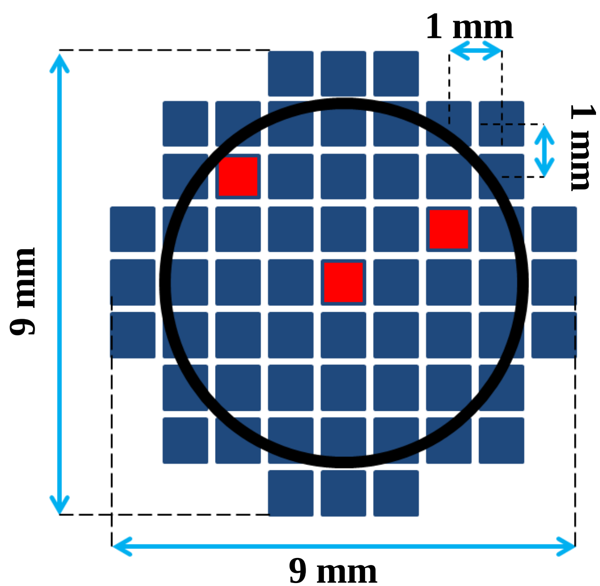
[2] "Wavefront aberration compensation with thermally deformable mirror"
B Canuel *et al* 2012 *Class. Quantum Grav.* **29** 085012

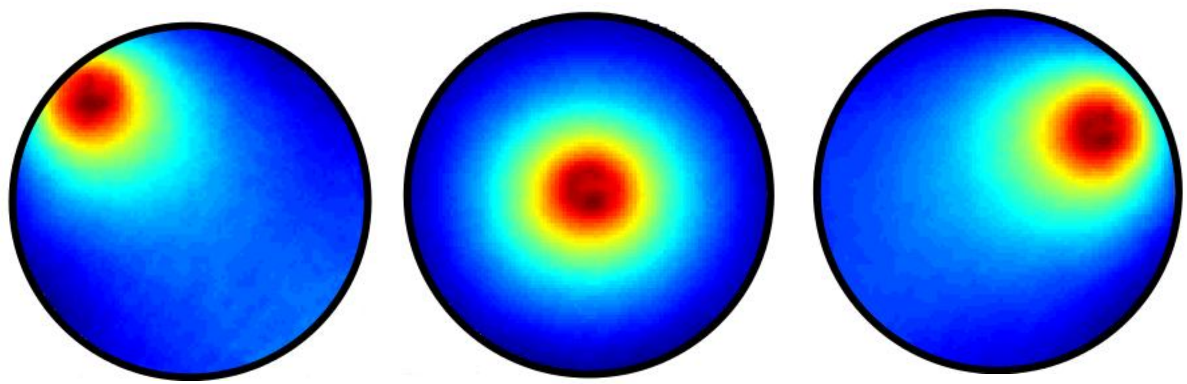
Experimental setup

In-air experiment

- Laser beam @ 1064 nm
- Fused silica standard dielectric mirror 2”
- Resistors in contact with the HR coating of the mirror
- Phase measurement with a wavefront sensor (abs. accuracy rms λ/100)







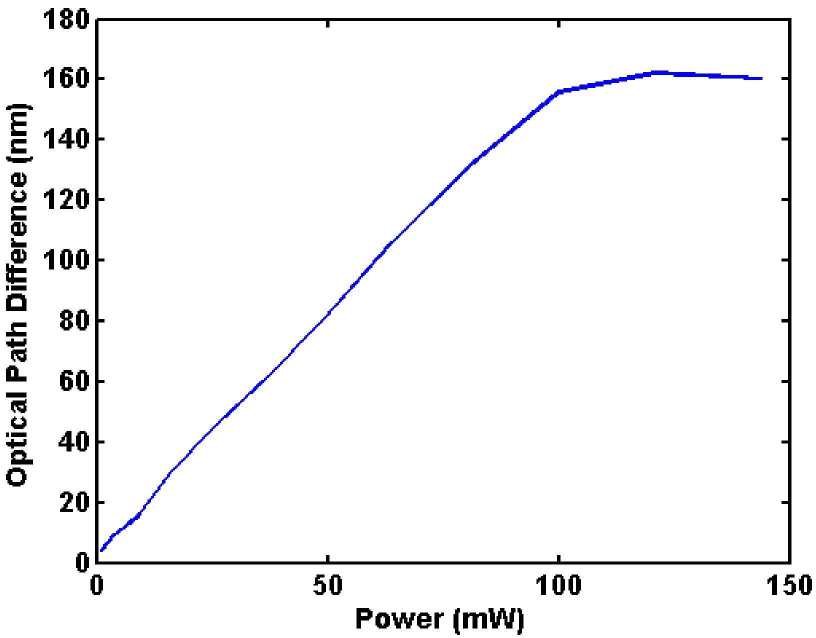
Experimental phase images

→ Local control of the wavefront by resistor actuation

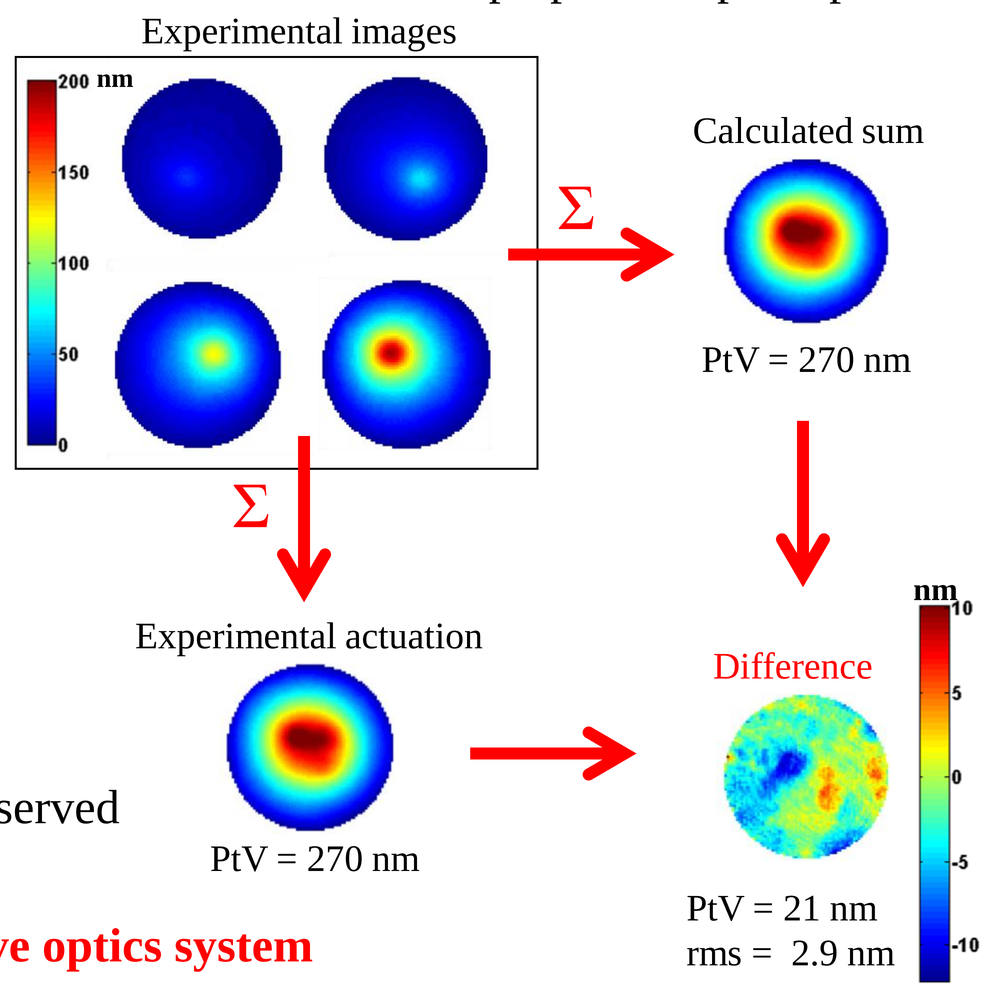
Experimental setup

Mirror response

- Linearity with power



- Verification of the superposition principle



- Time response of a few seconds :

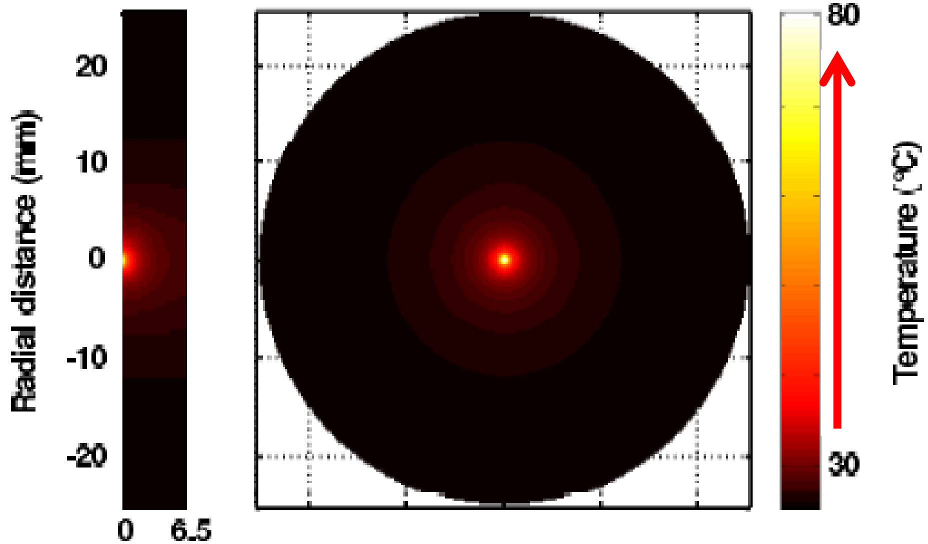
  time constant ~ 4s and no hysteresis observed

→ Possible use of the TDM as an adaptive optics system

Experimental setup

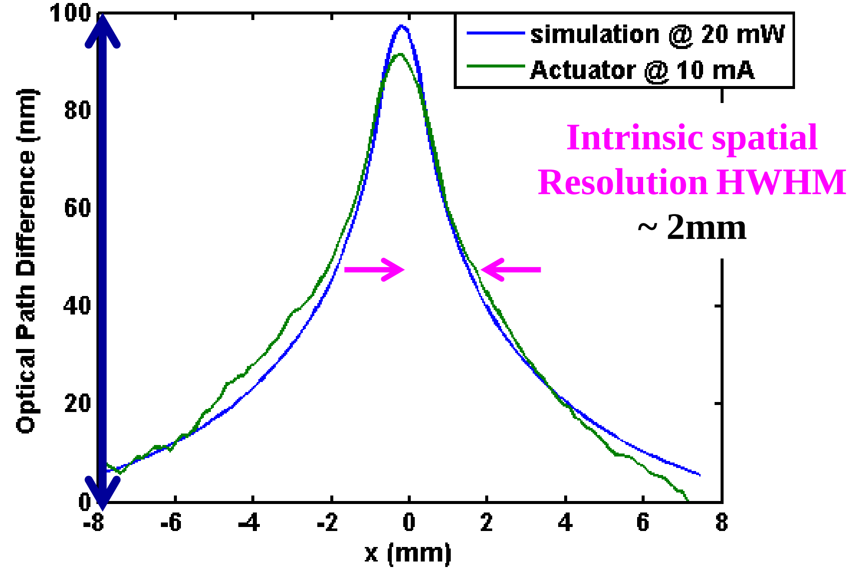
Simulations by Finite Element Analysis

➢ Temperature diffusion in the mirror substrate for a heating surface of 1 mm²



Temperature profile for 100 mW actuation

➢ Comparison of the OPD between simulation and experiment



Optical path difference (OPD)
~ 100 nm

→ Good agreement with experimental results : possibility of modeling an ideal TDM

How to perform
correction of low-order aberrations

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EUROPEAN GRAVITATIONAL OBSERVATORY

How to find the actuator values

Distorted wavefront $\omega_{distorted}$ → TDM → Corrected wavefront $\omega_{correction}$

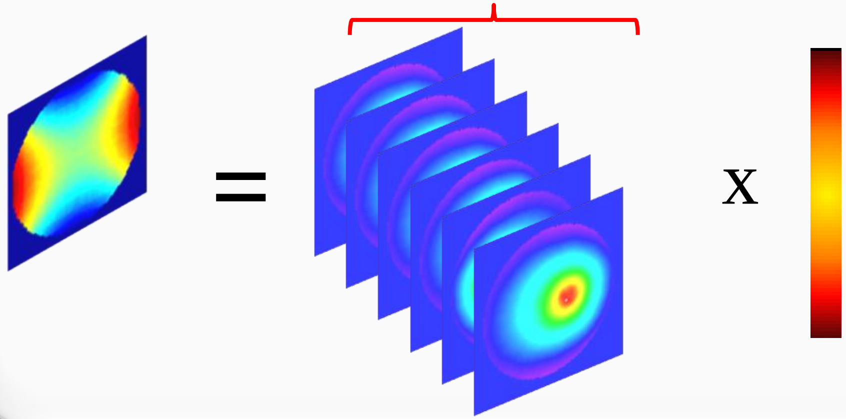
Distorted wavefront → Wavefront Sensor → Computation of the correction → TDM

Open control loop in adaptive optics

$$\omega_{correction} = -\,\omega_{distorted}$$

Use of the influence functions

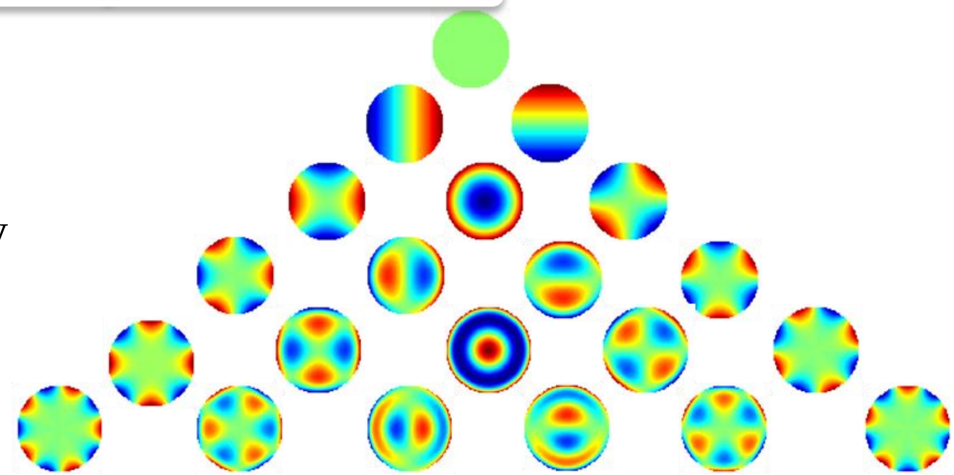
Distorted wavefront = **Interaction Matrix** (61 actuators x Zernike coefficients) x **61 actuation values**



$$actuation\ values = \begin{pmatrix} Interaction \\ Matrix \end{pmatrix}^{-1} \cdot \omega_{correction}$$

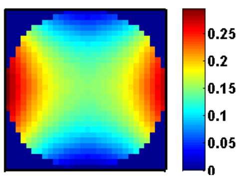
→ Easy and fast calculation for correction of large number of Zernike modes

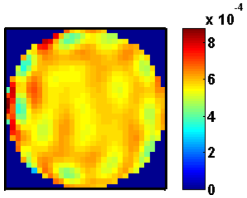
Correction parameters

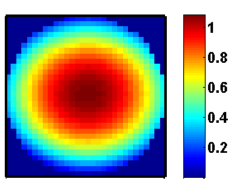


- **Zernike polynomials**
  orthogonal basis to describe
  the aberrations in spherical geometry

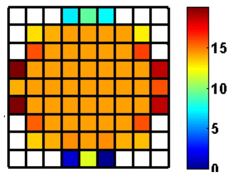
- Performance described by :







- **Dynamic range**
  PtV amplitude of the zernike mode limited
  by the maximum value of actuation ⟶



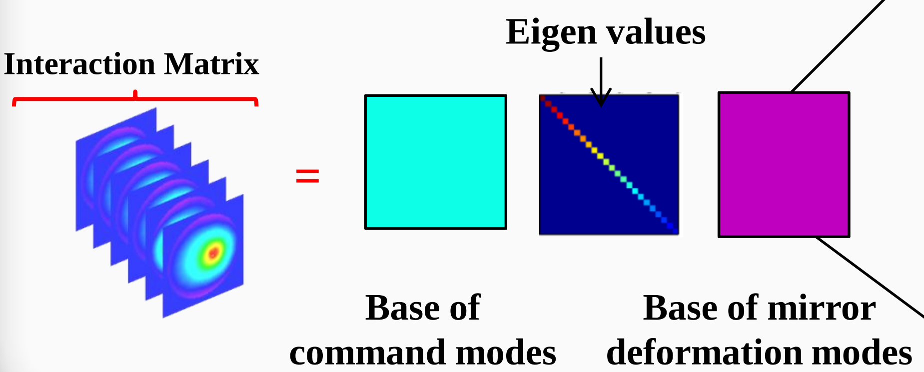
- **Residual error**
  rms value of the residual error limited by the footprint of the actuators

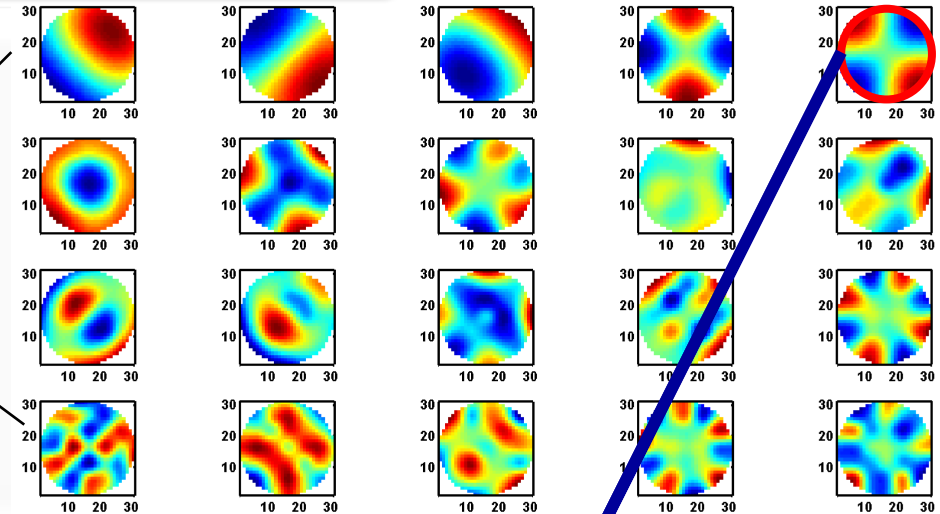
- **Induced focus**
  unwanted focus generated by this type of actuators, has to be removed

→ Characterisation of the TDM performance by ability to produce Zernike modes

Eigen modes of the mirror

Singular Value Decomposition

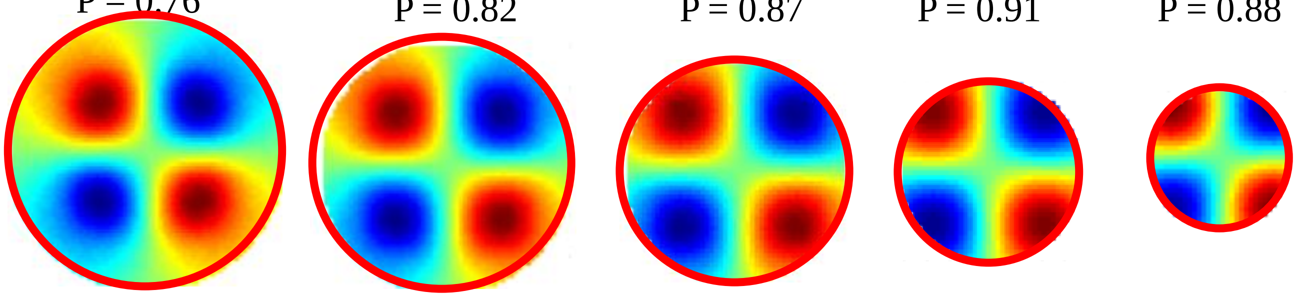


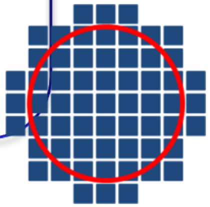


- Comparison of each eigen mode with the corresponding Zernike
  - **Purity** = Indication of the ease to reproduce the Zernike mode

Example with mode 5

Ø = 14 mm	Ø = 12 mm	Ø = 10 mm	Ø = 8 mm	Ø = 6 mm
P = 0.76	P = 0.82	P = 0.87	P = 0.91	P = 0.88





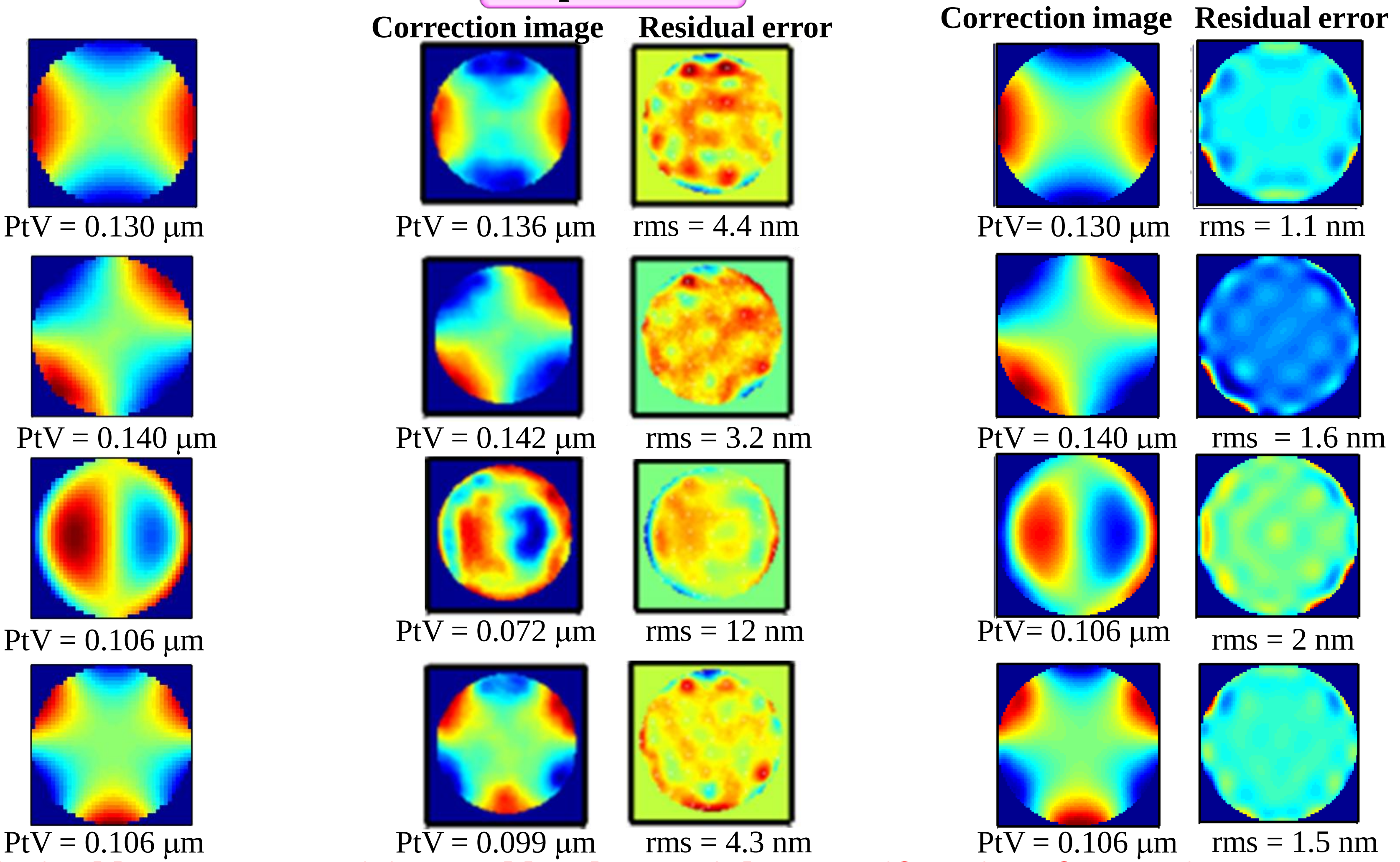
→ **Choice of the pupil size according to the maximum value of the purity**

TDM performances

Experimental results

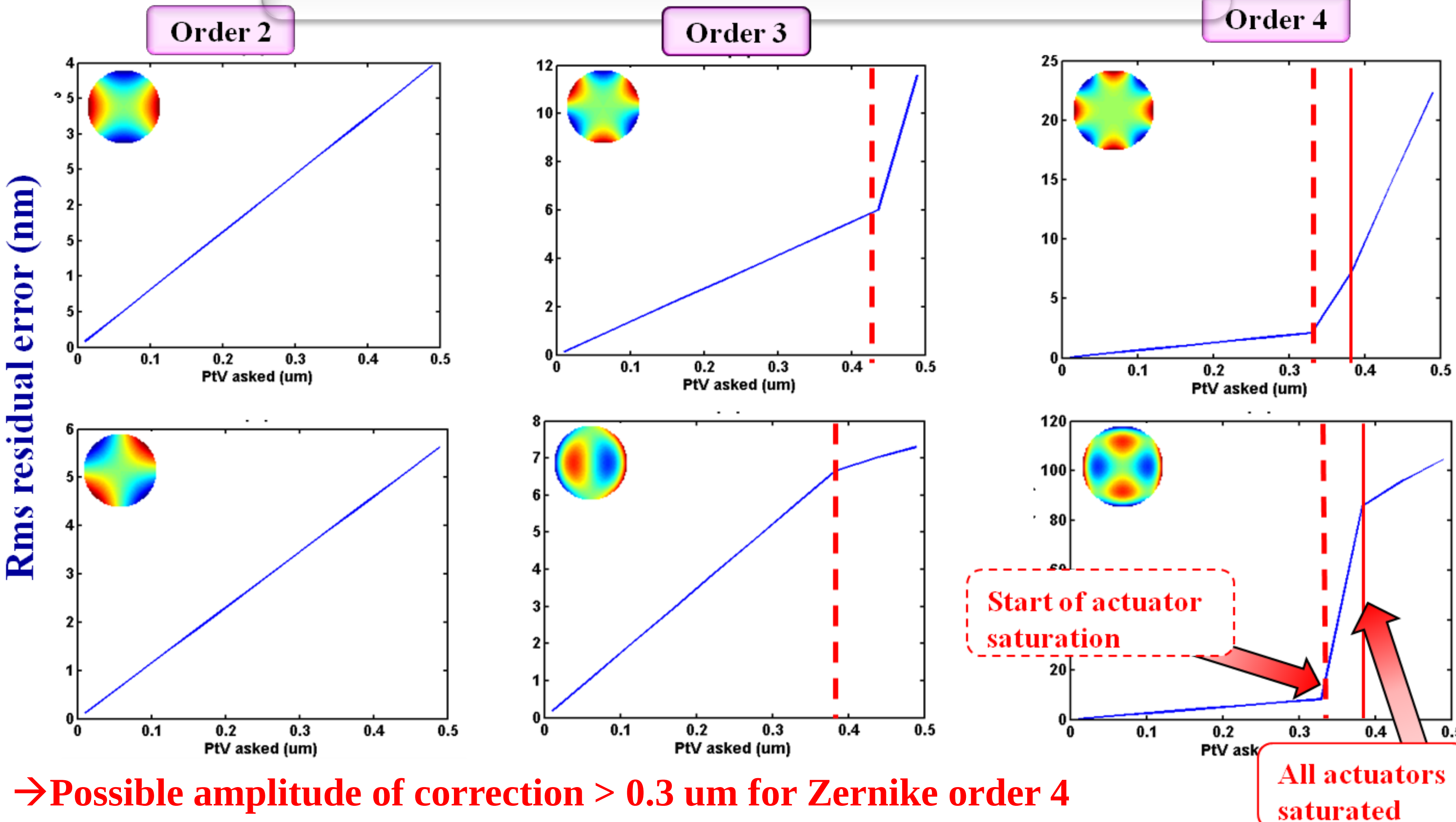
Closed-loop on first Zernike modes

Command | **Experiment** | **Simulation of ideal TDM**



→ Limited by sensor precision and by the spatial non uniformity of actuation

Rms value of error vs. Amplitude of correction
Simulation results

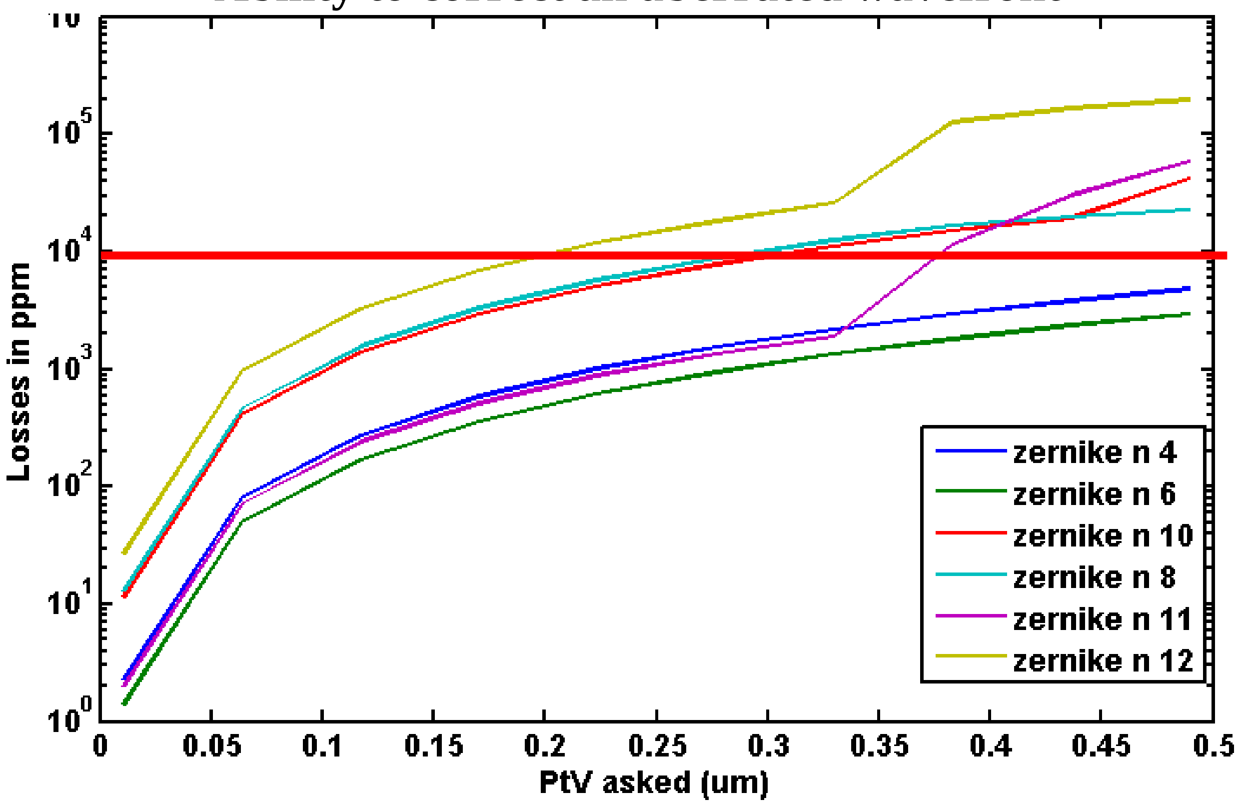


→**Possible amplitude of correction > 0.3 um for Zernike order 4**
→**Value of the focus to remove from infinity to 100 m**

Losses and weightening
Simulation results

- Matching requirements for the injection system of Advanced Virgo : Mode matching ≥ 99%

Ability to correct an aberrated wavefront



→ Losses meet the requirements in the dynamic range of the first order aberrations

Possible improvements

- Improvement of the dynamic range by:
  - Better thermal contact
  - Change substrate material
  - Improvement of power coupling in the mirror substrate

- Reduction of the residual rms value by:
  - Increase of actuator density
  - Improvement of homogeneity of the heating pattern

Conclusion

- **First prototype under characterization**

  Innovative device with a lot of great advantages:

  - Not limited by electronic noise
  - Vacuum compatible
  - Low cost and compatible with use of standard mirrors
  - Possible correction of first Zernike modes with a good precision

Next steps: Complete the experimental characterization
Experimental optimisation of cavity matching
Tests under vacuum

Possible applications

- Injection system of Advanced Gravitational Wave Detectors
- Output mode cleaner optimisation of matching
- Optimised mode matching for squeezed light injection system