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PIANO NAZIONALE DI RIPRESA E RESILIENZA

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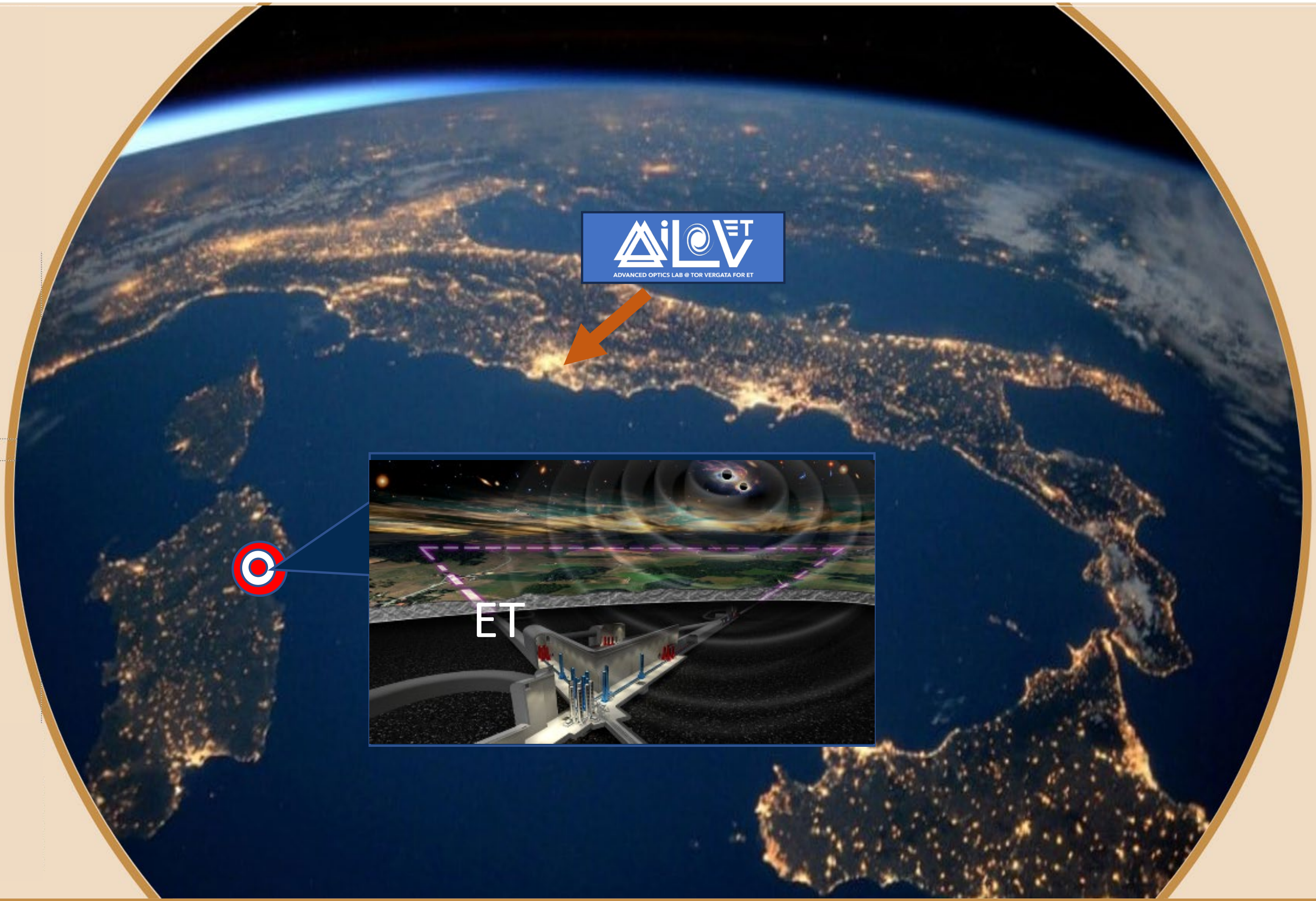
Mitigation of non-axisymmetric residual wavefront distortion in core optics



M. Cifaldi and L.A. Corubolo

On behalf of ET Roma Tor Vergata

XV ET symposium
26th-30th May 2025

Outline

- **Wavefront aberrations and the axisymmetric corrections**
  - The necessity of a strategy for the non-axisymmetric correction

- **The problem of point defects**
  - The importance of a mitigation strategy
  - Examples of point characterization and the correction strategy
  - The first actuator and the case of Virgo
  - The new test setup in Rome Tor Vergata: preliminary test and plans

- **The problem of non-axisymmetric Optical Path Length (OPL)**
  - The strategy of the Deformable Mirror
  - Deformable Mirror (DM) characterization
  - Modified Gerchberg-Saxton Algorithm (MoG-S)
  - Preliminary results

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Wavefront aberrations and Thermal Compensation System

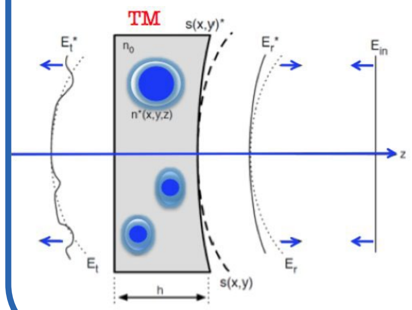
SOURCES

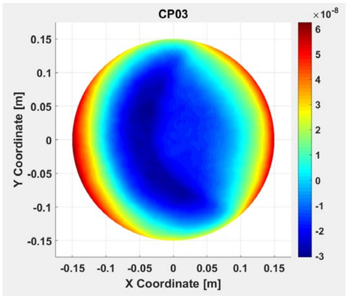
COLD DEFECTS
Imperfections in the production process of the mirrors

DYNAMICAL EFFECTS
Absorption of optical power in the coatings and substrates of the optics

EFFECTS

- Inhomogeneity of refractive index, impurities …
- Manufacturing errors (mismatch of Radius of Curvature (RoC), etc)

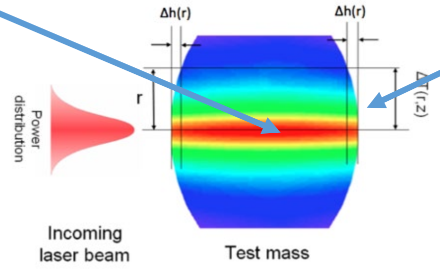




Thermal lensing

$$\Delta OPL_T = \frac{dn}{dT}\int_S \Delta T\, ds$$

OPL distortions due to dependence of refractive index from temperature variation



Thermo-elastic effect

$$\Delta OPL_R \approx 2\alpha \int_0^h \Delta T\, dz$$

Change of RoC of mirrors due to the absorption of laser power→ non-zero thermal expansion coefficient

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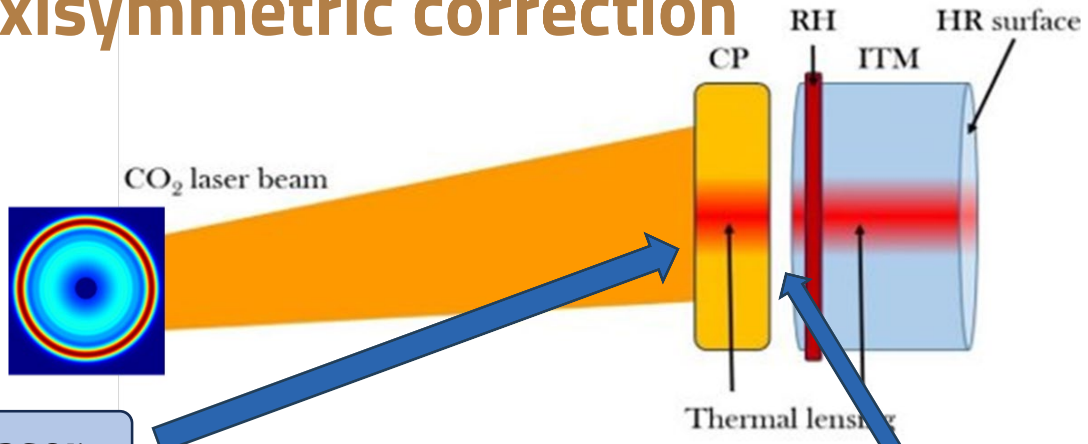
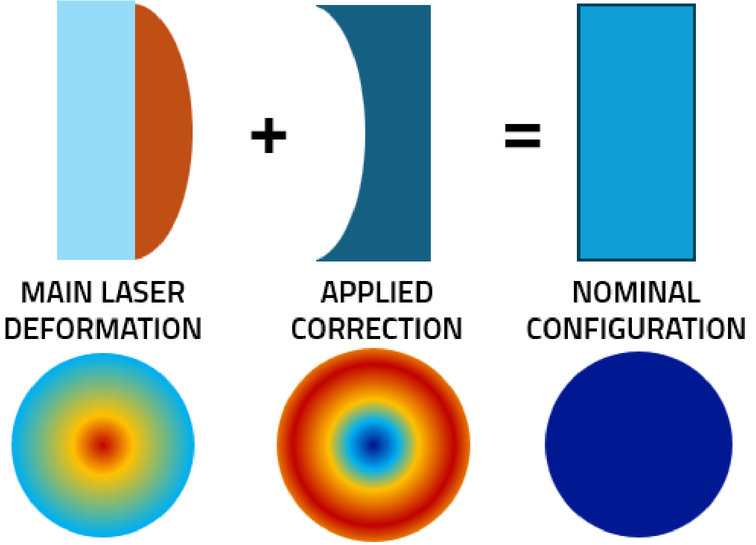
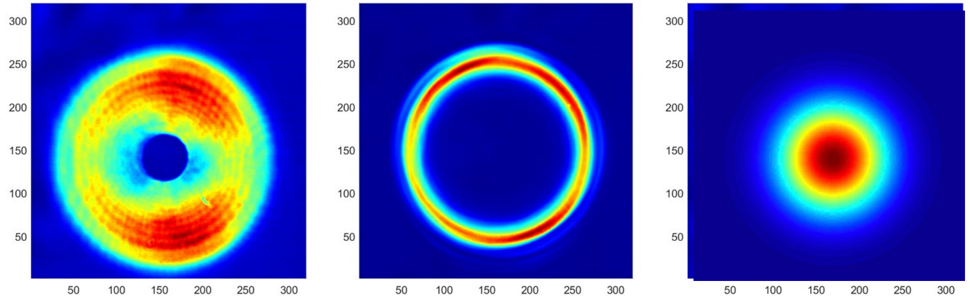
The axisymmetric correction



CO2 laser projectors

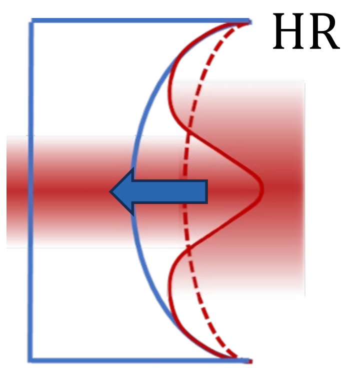
Ring Heater





Inner & outer DAS

Central Heating



The actual TCS setup provides the needed correction → upgrades are ongoing

Compensation produces a **non-spherical residual deformation** and **the presence of defects** on the HR surface requires new technologies

The non-axisymmetric correction

Non-axisymmetrical aberrations

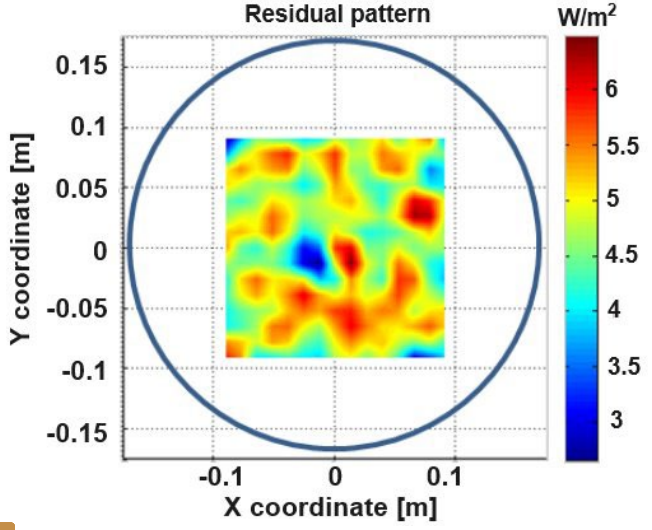
Residual OPL

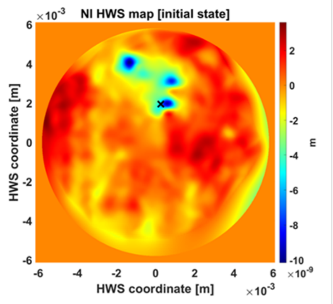
Point defects

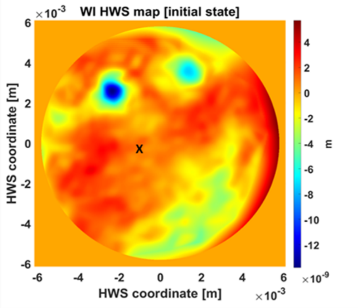
Action with CO2 laser on the Compensation Plate (CP)

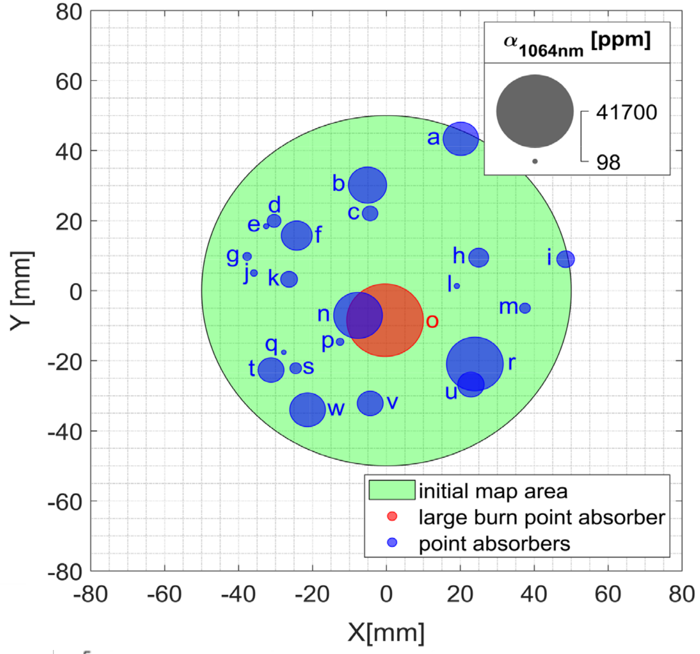
Action with thermal radiation on the High-Reflectivity (HR) surface

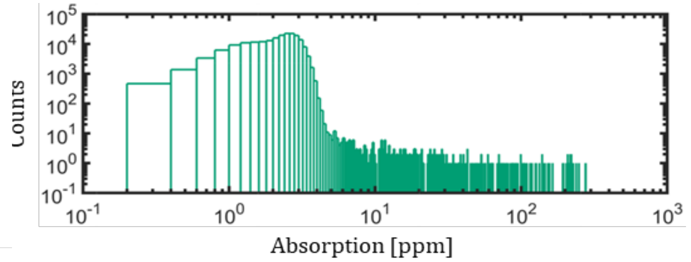
Effect present both in thermo-elastic deformation than in thermal lensing











McGhee, Zhang, Billingsley, DCC: G2401657

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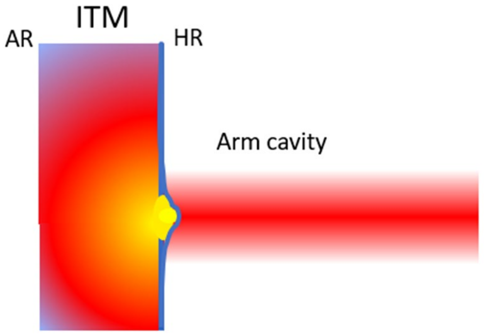
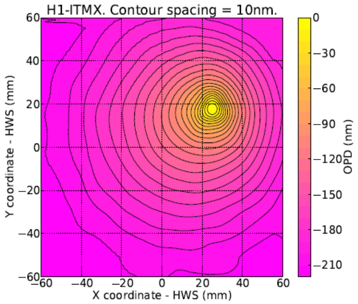
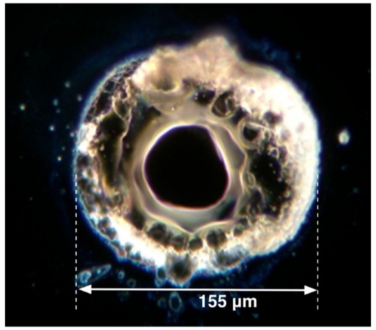
The problem of point defects

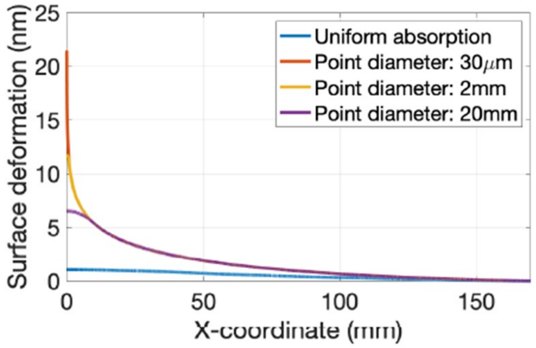
[arXiv:2101.05828]

Discovered during the O3 observing run on both LIGO and Virgo test masses (TM) after the increase of the ITF laser power







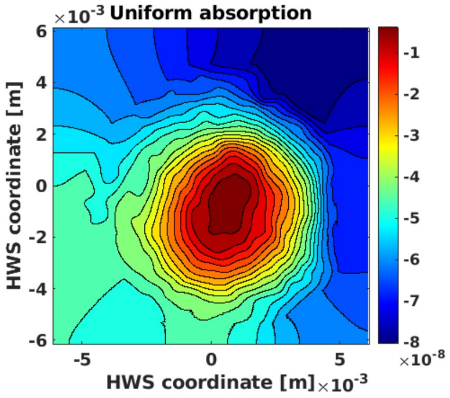


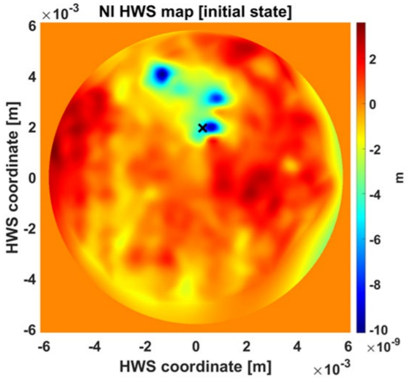
Characteristics:

- Localized small
- Randomly present on the HR mirror surfaces
- Highly absorbing
- Mainly embedded in the coating
- Can not be cleaned
- Composition of high concentration of Aluminium

Effects of their presence:

- Scattering into Higher Order Modes (HOM)
- Increase of round-trip losses
- Limits interferometer sensitivity



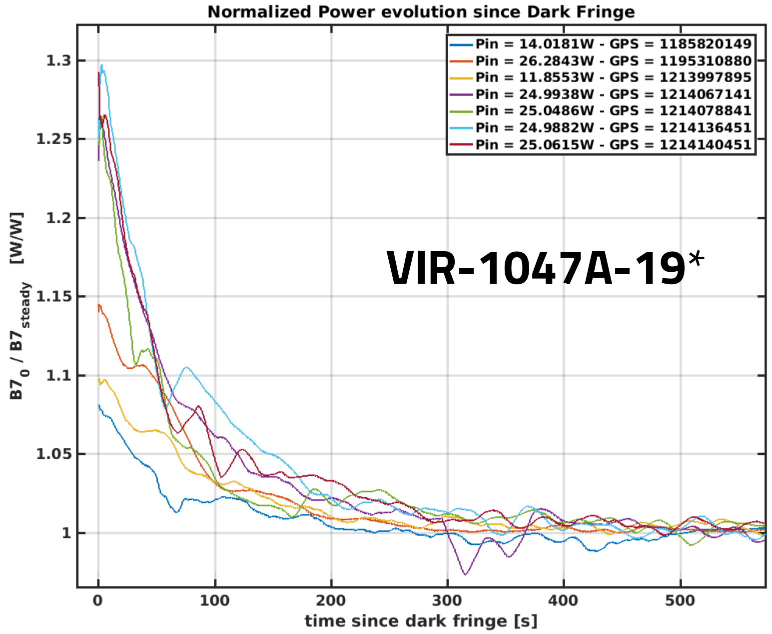


The point defects and the power

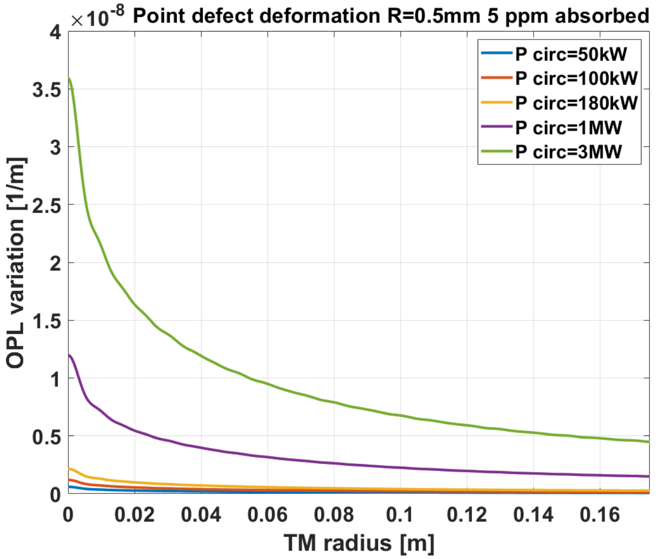
- **Point defects are strongly dependent by the fraction of absorbed power and position on the HR surface**

What we learn with the experience:

- The origin of the point is still unclear → it is not solely due to coating imperfections
- Detection facilities capable of identifying the presence and location of the point before installation are essential
- The power circulating in the cavities provides new insights → observable after the test mass installation
- Replacing the test mass is a complex procedure → a well-defined compensation strategy is necessary



*Allocca, Chiummo, Ruggi, Yamamoto



Reaching its full potential requires ET-HF to adopt a well-defined approach to handle point defects

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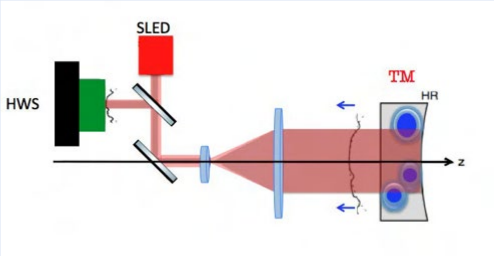
The point defects: characterization and diagnostic

Procedure steps:

HWS acquisition with on-axis setup



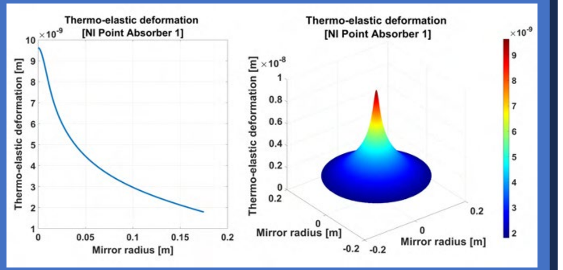
HWS wavefronts analysis

- Mirror center position
- Point position
- Point characteristic (deformation size, time evolution)

Parameter estimation

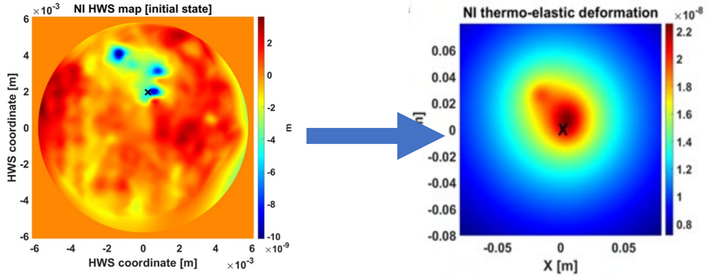
- Absorbing coefficient in ppm
- Absorbed power
- Point position

FEA simulations



Estimated parameters with the studies on the Virgo ITM:

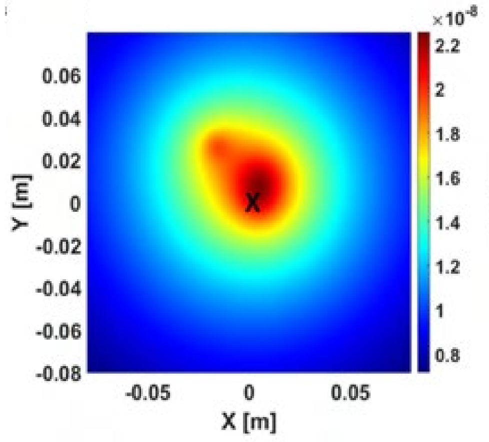
- Thermo-elastic deformation: 1-12 nm
- Thermalization times: 5 minutes
- Absorbed power (Pcirc=100kW): up to 40 mW (max 18ppm)



ITALY Einstein Telescope

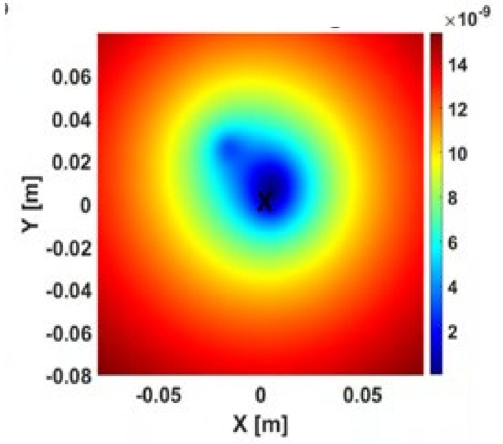
The point defects: correction principle

1. Evaluation of the thermo-elastic deformation



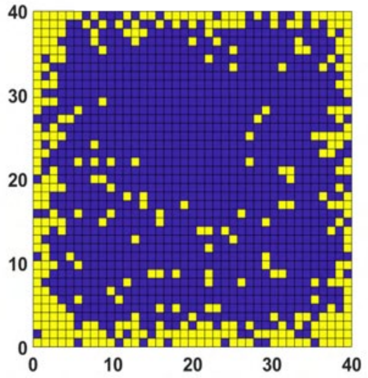
Point defects characterization and Finite Element Analysis (FEA) analysis required

2. Evaluation of the corrective target deformation



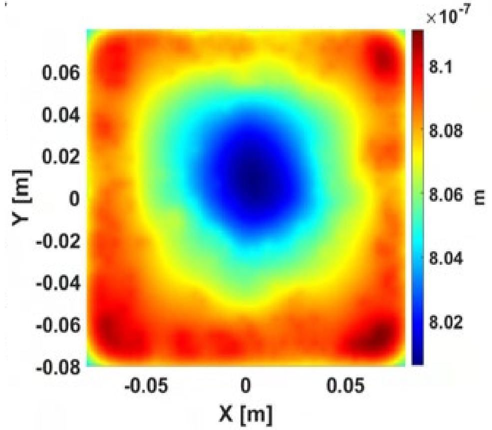
The theoretical correction target is defined to restore a 'flat' condition, up to a normalization factor

3. Recovery of the mask pattern



Optimized iterative algorithm by minimizing the Gaussian-weighted RMS Key issue: accuracy and power efficiency

4. Evaluation of the reproduced corrective target



Quality evaluation through optical simulation with single cavity and full ITF

The point defects: the influence matrix formalism and the mask

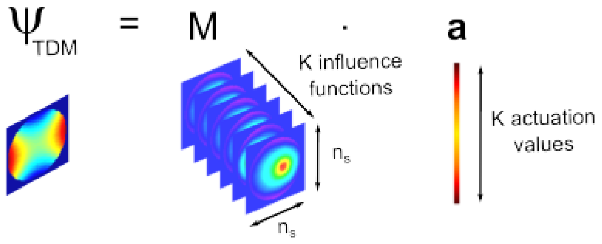
General idea: The corrective target will be reproduced through a binary mask illuminated by a thermal source. The mask holes act as a single actuator. The mask operation can be described with the influence matrix formalism.

Project of the **influence matrix**:

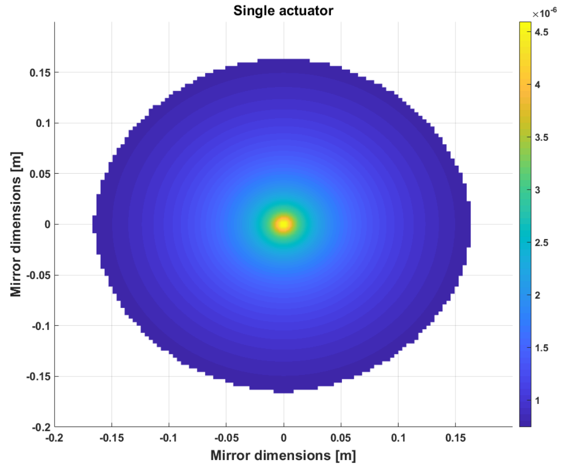
- Study of the single actuator influence function
- Study of the matrix geometry
- Implementation of the influence matrix and recovery of the actuation vector

$$\psi = M \cdot \vec{a} = \sum_{i=1}^{N} I_i(x,y)\, a_i$$
$$\vec{a} = (a_1, \dots, a_i, \dots, a_N)$$
$$min\|M \cdot \vec{a} - T\|_2^2 \quad \text{con} \quad a_i \geq 0$$

Actuation coefficients allowed: **0 or 1**



$$M_{2D} = \begin{bmatrix} I_1(1) & \cdots & I_i(1) & \cdots & I_K(1) \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ I_1(j) & \cdots & I_i(j) & \cdots & I_K(j) \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ I_1(n_s^2) & \cdots & I_i(n_s^2) & \cdots & I_K(n_s^2) \end{bmatrix}$$



- Influence function recovered both with FEA simulation (2D and 3D case)
- Squared and circular shape
- Different matrix geometry under test

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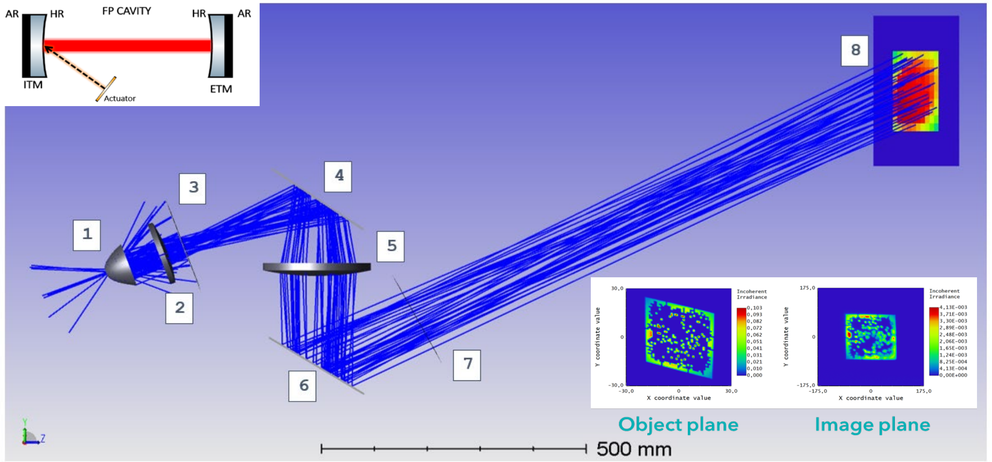
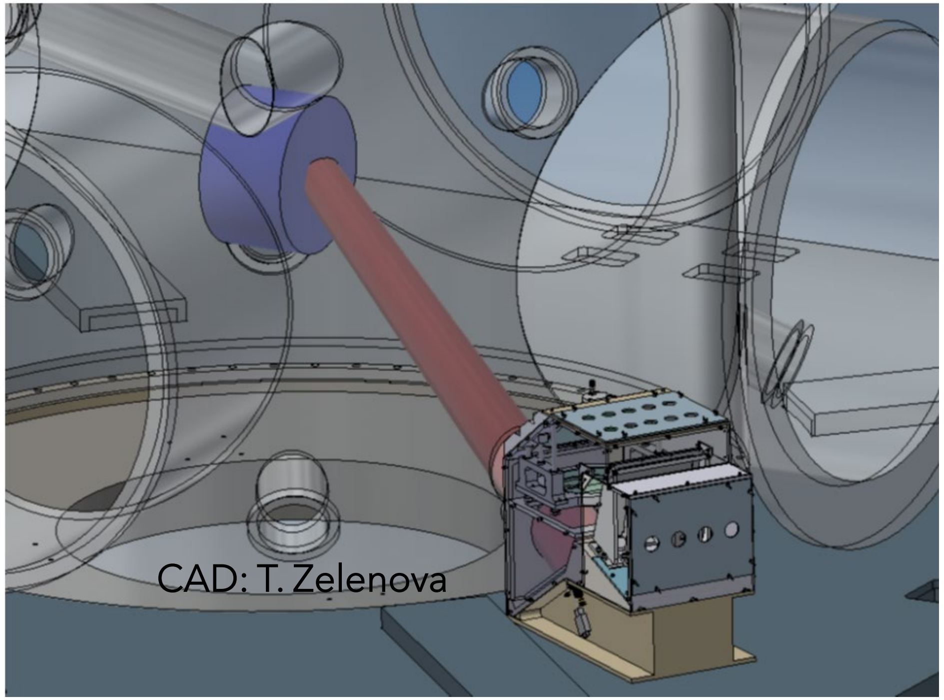
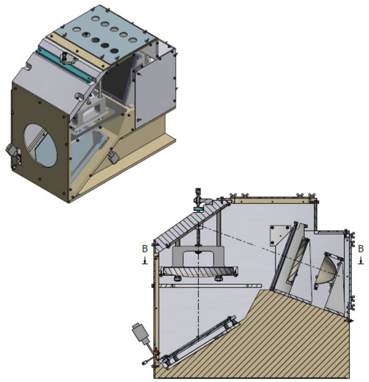
The point defects: the Virgo case

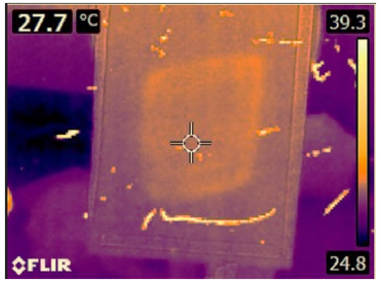
- **Virgo test mass present all Point Absorbers**
  - ➢ NI actuator installed
  - ➢ Other actuators to be assembled and installed before the end of 2025
  - ➢ Actuator alignment procedure under study
  - ➢ Other diagnostic studies on going

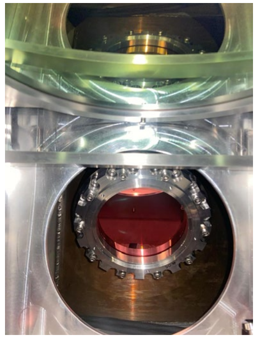


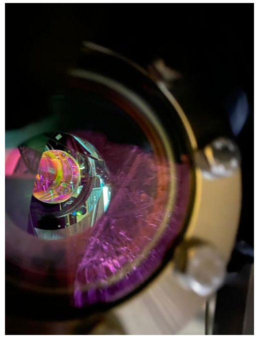
Components:
1: Parabolic reflector and ceramic heater
2: Focusing Germanium Lens (L1) (5")
3: Binary mask
4-6: Steering mirrors
5: Imaging Germanium Lens (L2) (8")
7: ZnSe viewport
8: Test Mass











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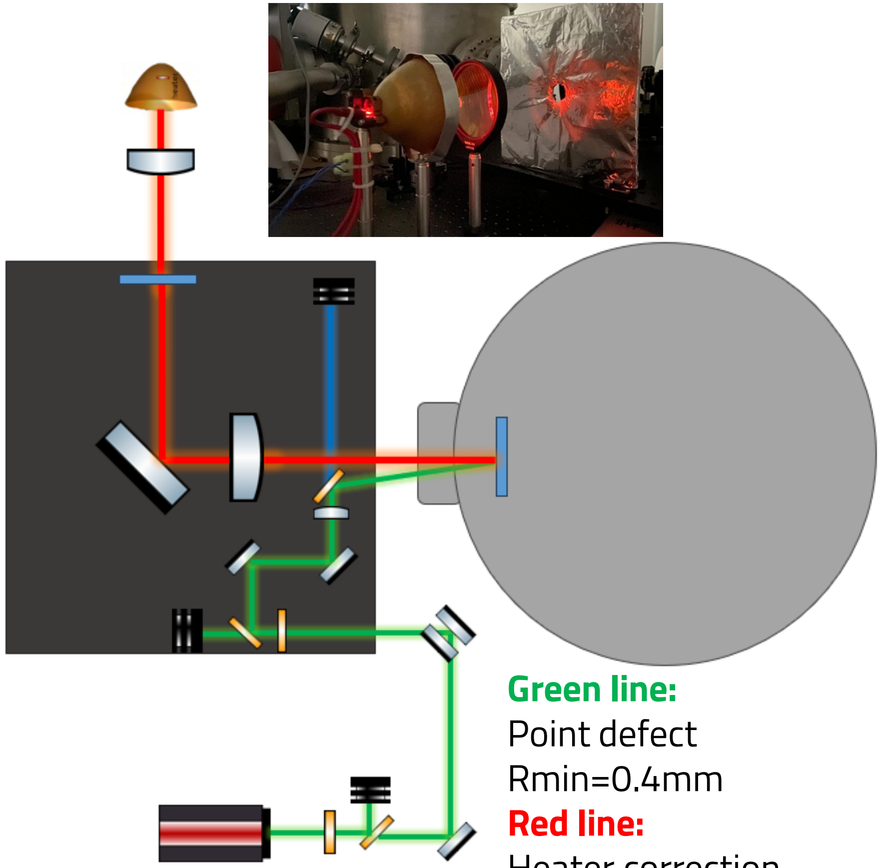
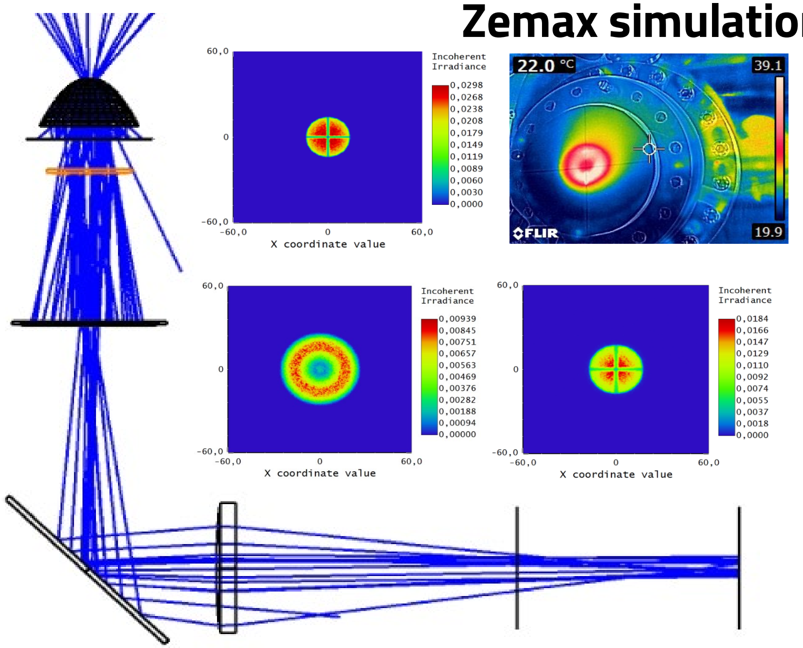
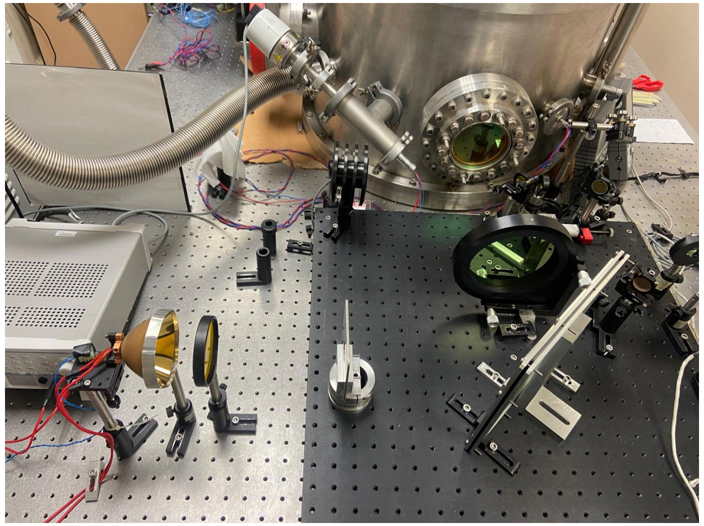
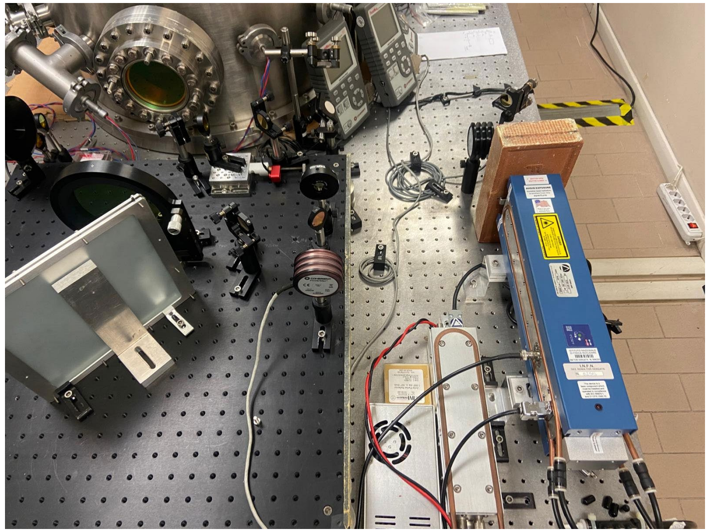
The point defects: Tor Vergata test setup



Zemax simulation







Green line:
Point defect
Rmin=0.4mm
Red line:
Heater correction
M=1.3

Setup goals:
- Test and optimization of alignment techniques pre-commissioning
- Reduction of the commissioning time
- Test of new mask and correction pattern
- Study of possible issues

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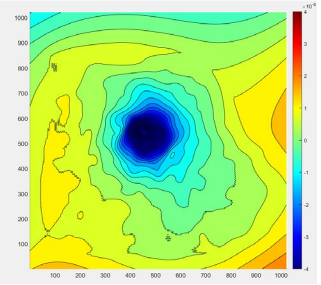
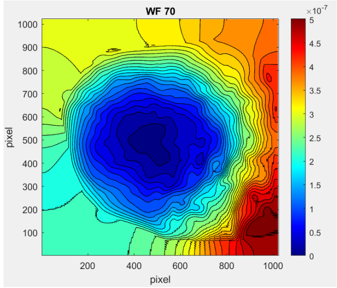
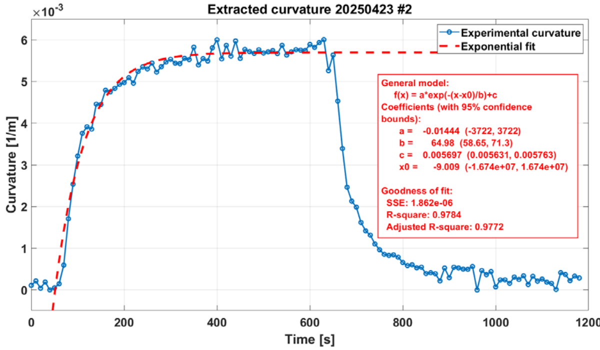
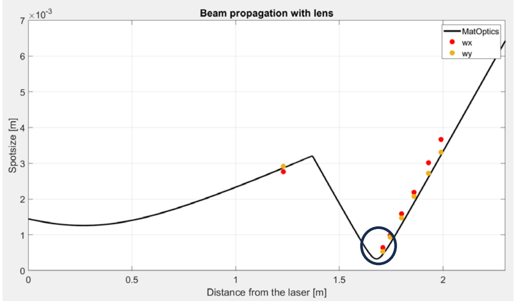
The point defects in ToV: characterization and preliminary results

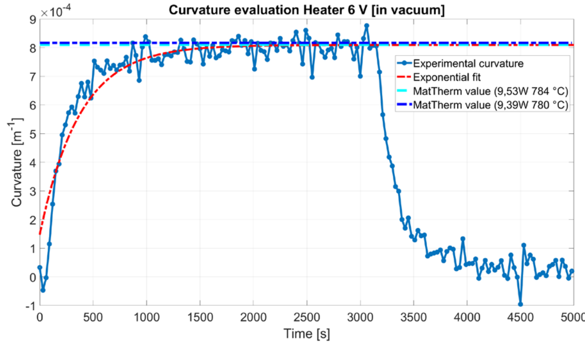
- **Point setup characterization**
  - ➢ Beam propagation and point dimension
  - ➢ Point position and effect
- **Heater setup characterization**
  - ➢ Heater temperature behaviour
  - ➢ Beam propagation
  - ➢ Alignment techniques
- **Planned test**
  - ➢ Study of the heater and point deformation together
  - ➢ Study of the point deformation in different CP positions
  - ➢ Study of the corresponding heater correction
  - ➢ Study and test of different mask geometry and patterns
  - ➢ Optimization of the point analysis procedure

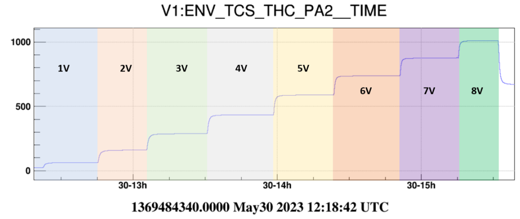


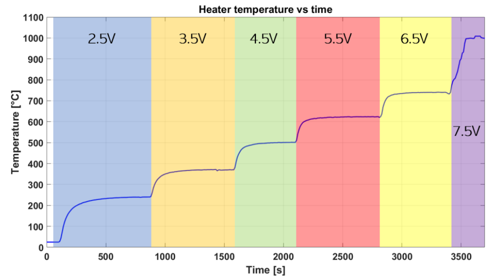










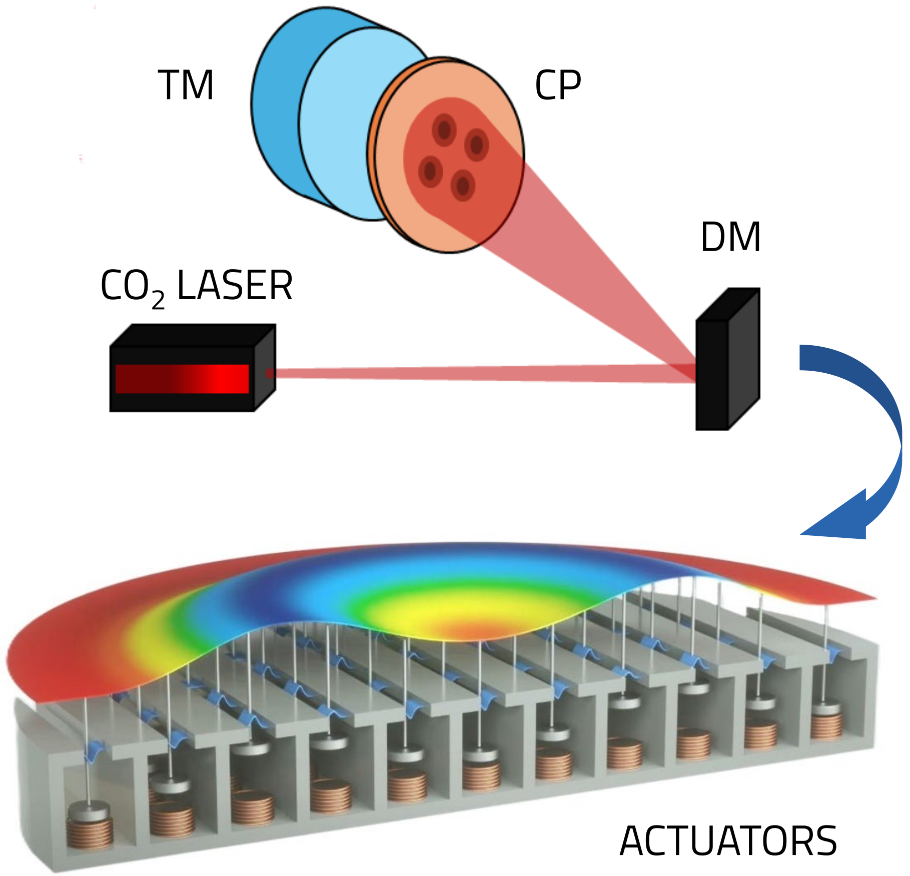


Deformable Mirrors: Working Principle

- **Problem**
  - variations in optical path due to temperature gradients and mechanical strains of TM (*thermal lens*) and *cold defects*.

- **Solution**
  - produce a suitable intensity pattern on the CP to introduce a complementary correction in TM's optical path. The correction is **static and adaptive**.

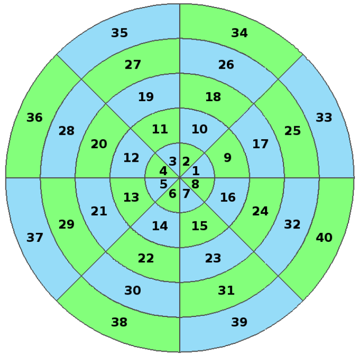
- **Method**
  - Deformable Mirror (DM) alters the phase of the probe CO_2 beam to reproduce the required intensity pattern on the CP.

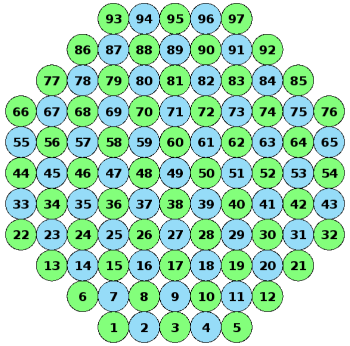


Don't miss the details — check the poster #84!
TDS: ET-0185A-25

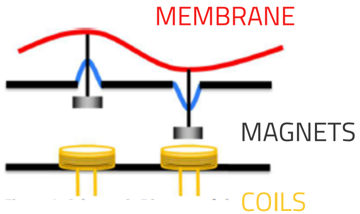
DM: Main Features and Influence Functions

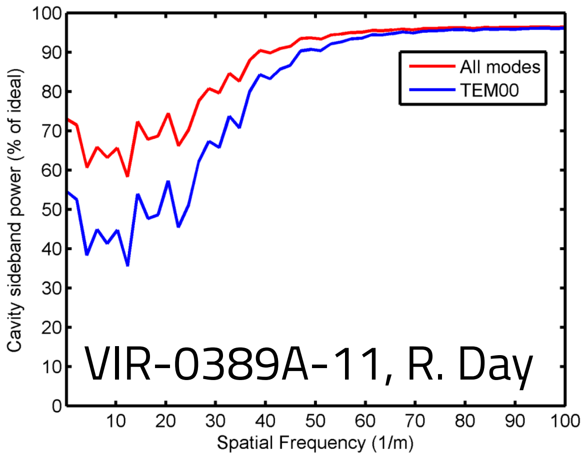
- **DMs history at Tor Vergata…**
  - ➢ ***Titan*** (by ®Adaptica, 144 piezo-electric actuators with a circular layout) **2016**
  - ➢ ***DMP40*** (by ®Thorlabs, 40 piezo-electric actuators with a circular layout) **2019**
  - ➢ ***DM97-15*** (by ®ALPAO, 97 magnetic actuators with a grid layout) **2019**
  - ➢ ***DM192-15*** (by ®ALPAO, 192 magnetic actuators with a grid layout) **2024**





- **Characteristics of DM192-15 (by ®ALPAO)**
  - ➢ 192 magnetic actuators
  - ➢ **Pupil diameter: 21 mm**
  - ➢ **Pitch: 1.5 mm**
  - ➢ Gold coating
  - ➢ Stroke: 4.5 μm
  - ➢ High stability option (static correction!)



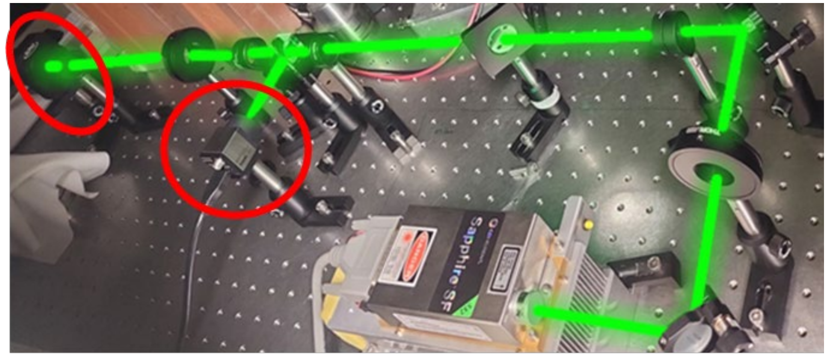


AdV+ case:

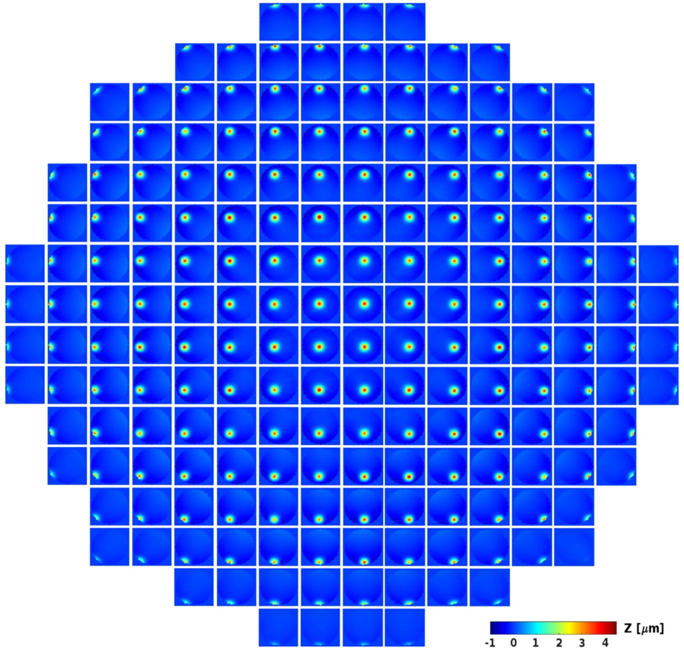
$$f_{CP} = f_{PITCH}\,\frac{d_{DM}}{d_{CP}} = 40\ \mathrm{m}^{-1}$$

DM: Characterization in Phase

- **Measure the IFs**
  - We are currently using a green laser (532nm) to control the DM phase.
  - A Shack-Hartmann (SH) sensor is positioned on the DM's image plane, looking at the phase variation induced by each individual actuator (IFs).



[following C. Taranto's PhD thesis]



- **Evaluate the DM performance**
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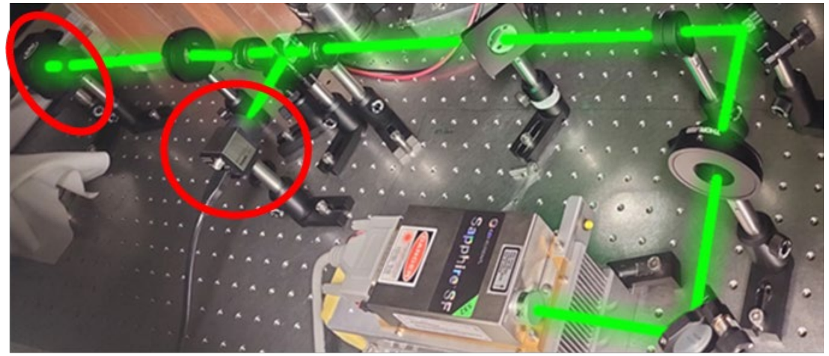

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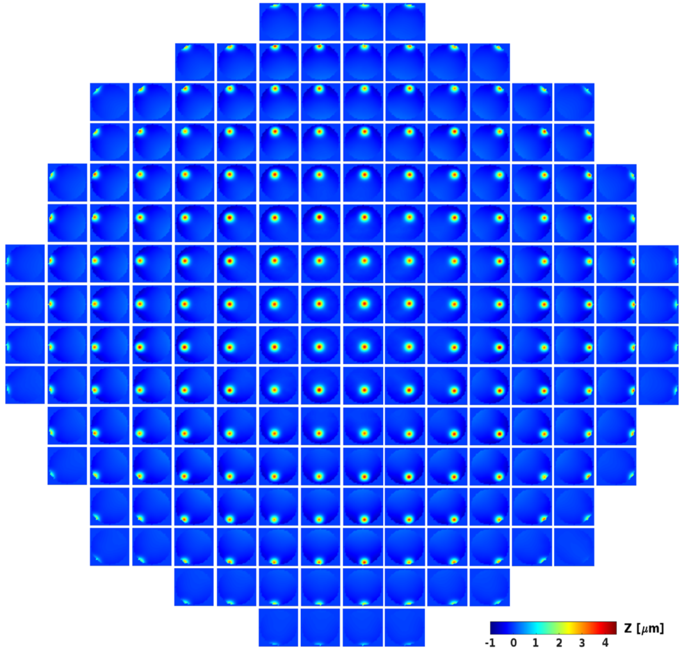

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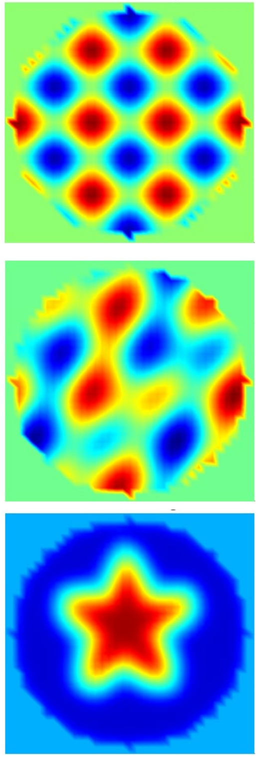
TARGET PHASE



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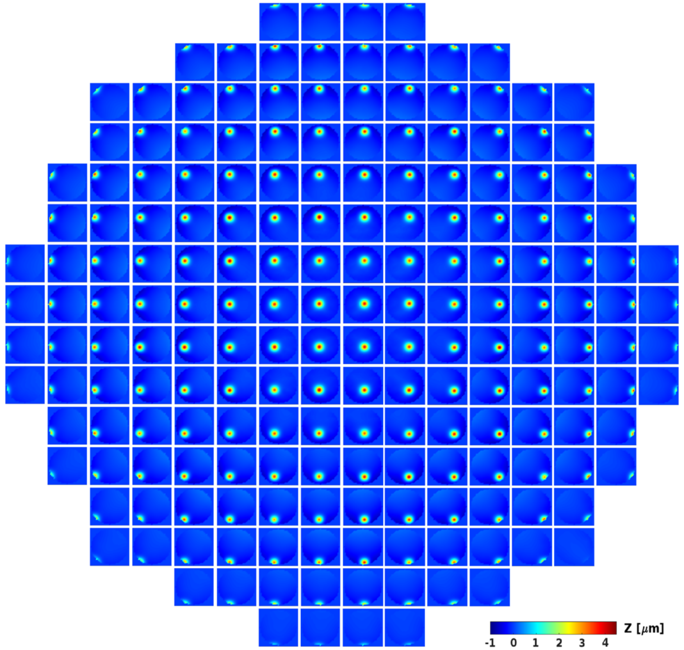

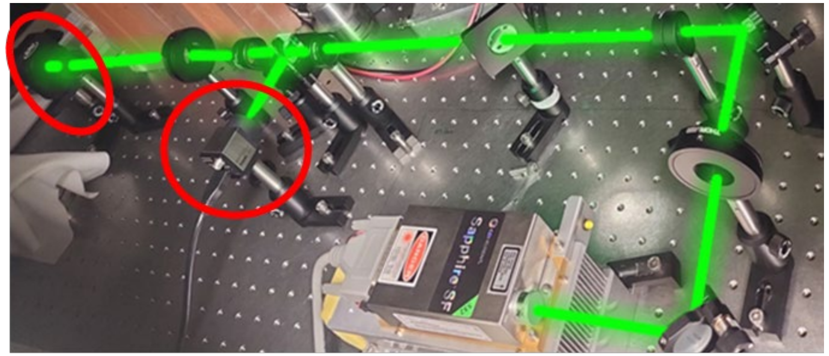

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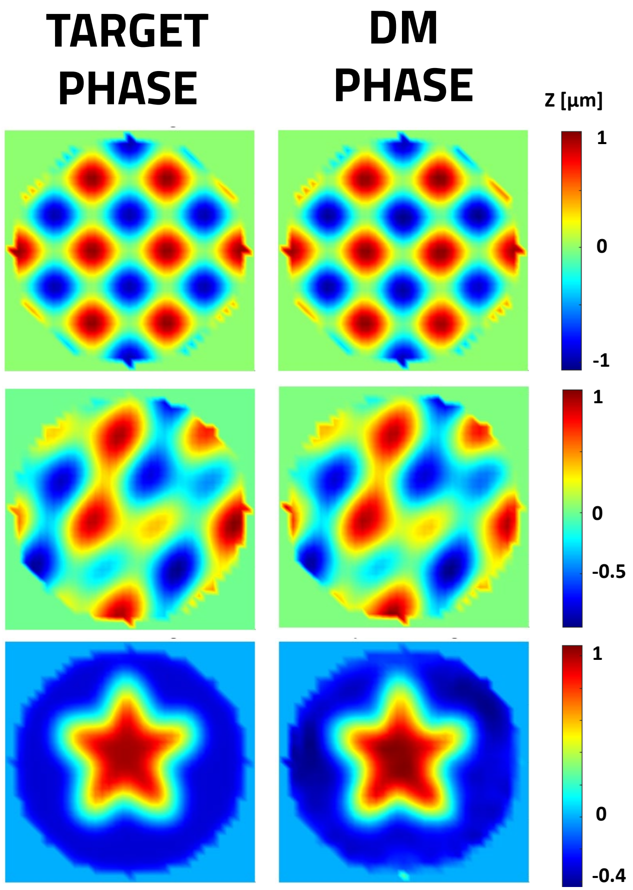
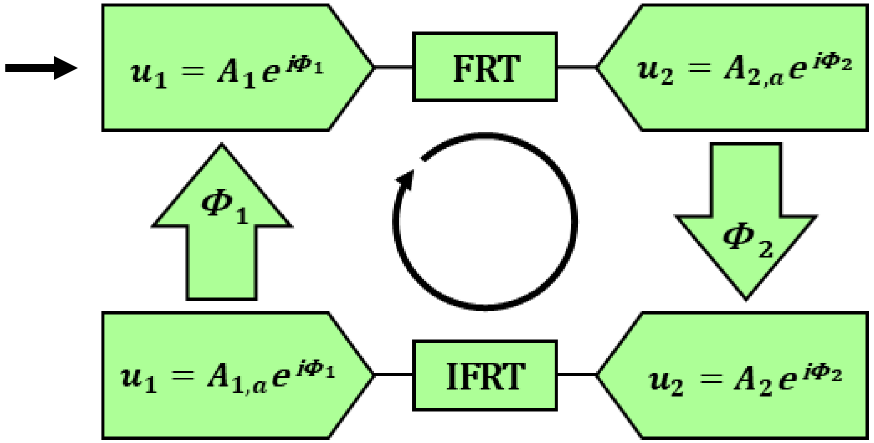
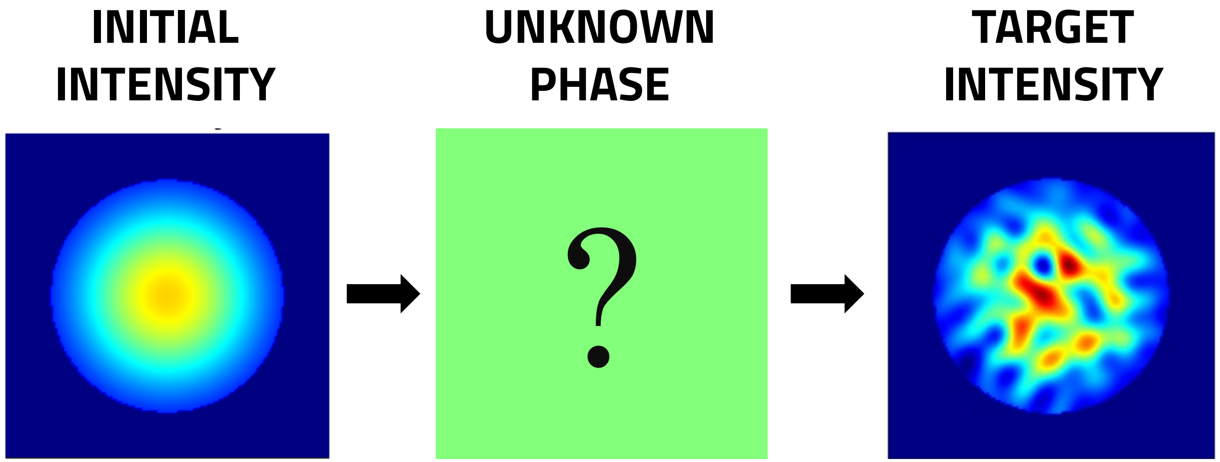


DM: Modified Gerchberg-Saxton Algorithm (MoG-S)

- **Phase retrieval problem**
  - recover the unknown phase starting from two measurements of intensity (initial and target) at distance z from DM.
  - We use a MoG-S, where the standard Fourier transform is replaced by the Fresnel transform.



[arXiv:1711.01176]



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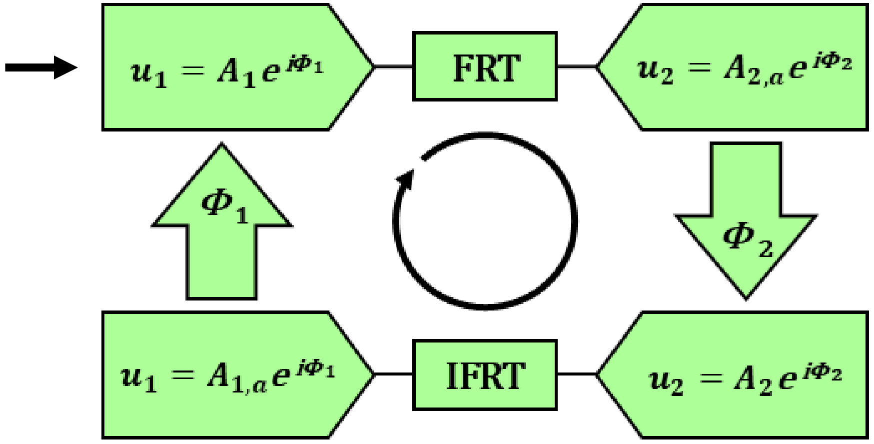
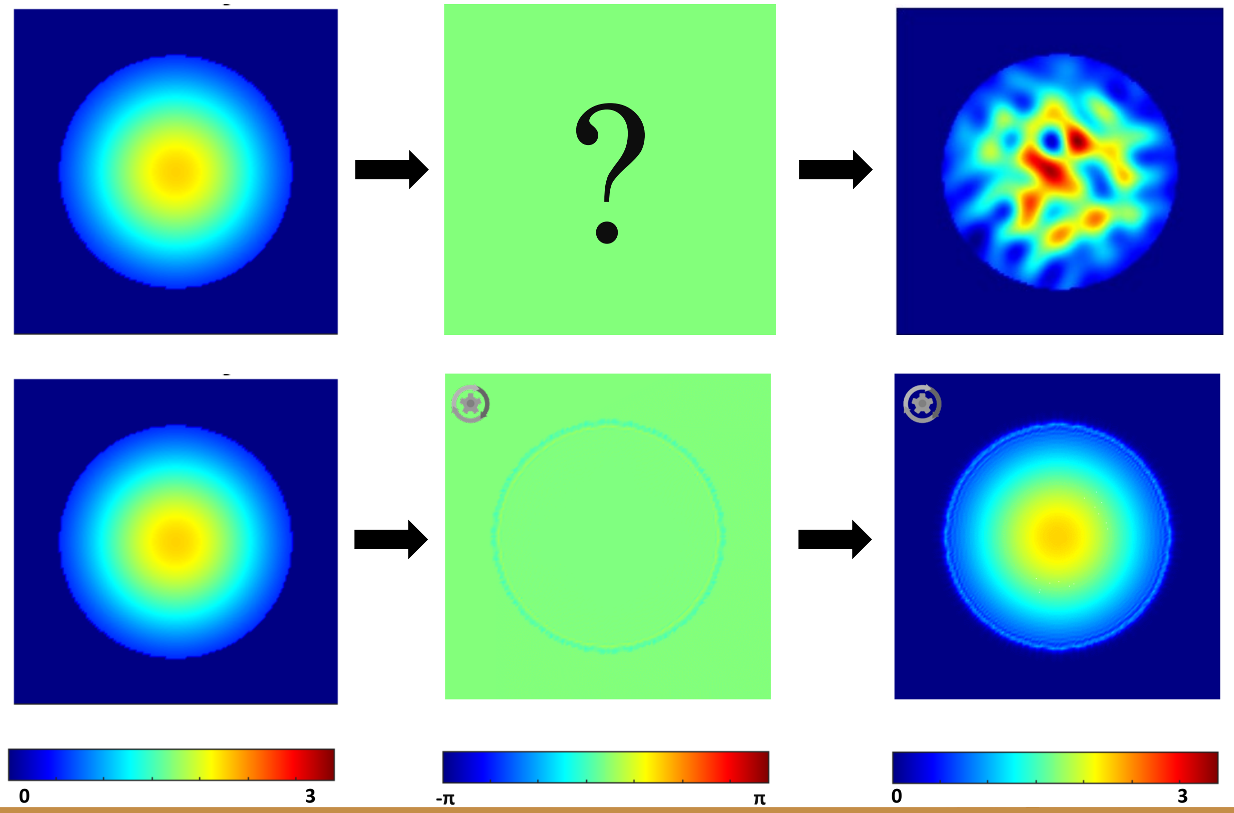


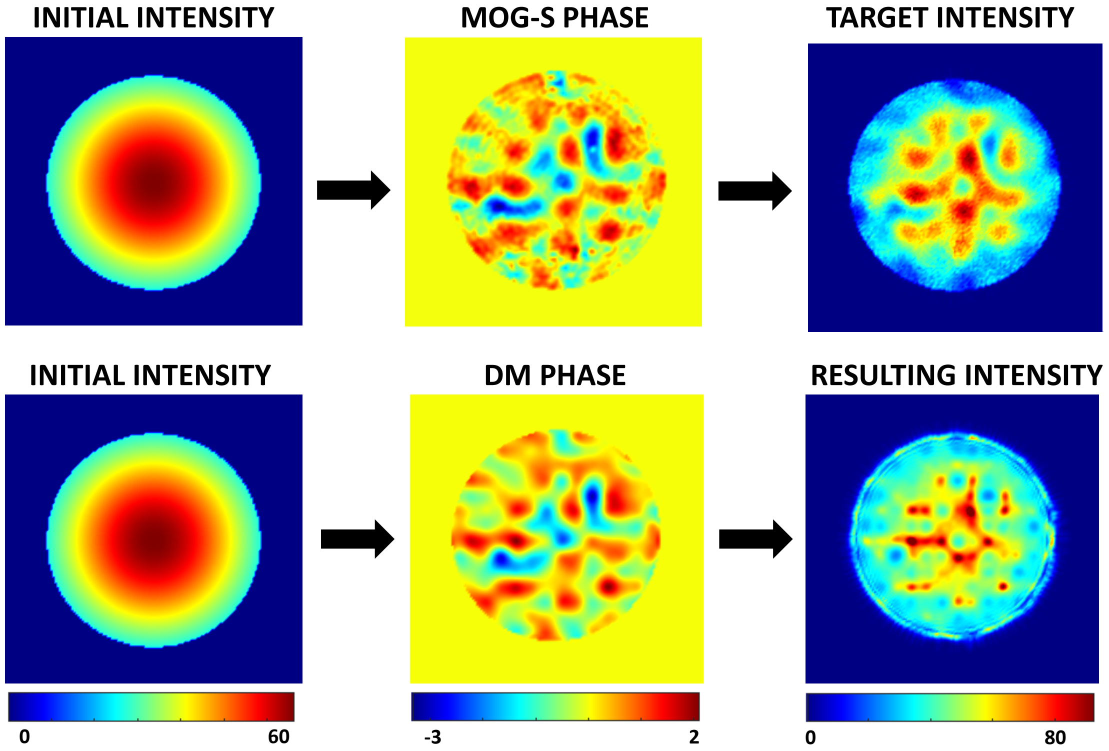
[arXiv:1711.01176]

INITIAL INTENSITY | UNKNOWN PHASE | TARGET INTENSITY



DM: Actuation in Intensity

- **Can DM reproduce the target intensity?**
  - ➢ Simulation results are promising:



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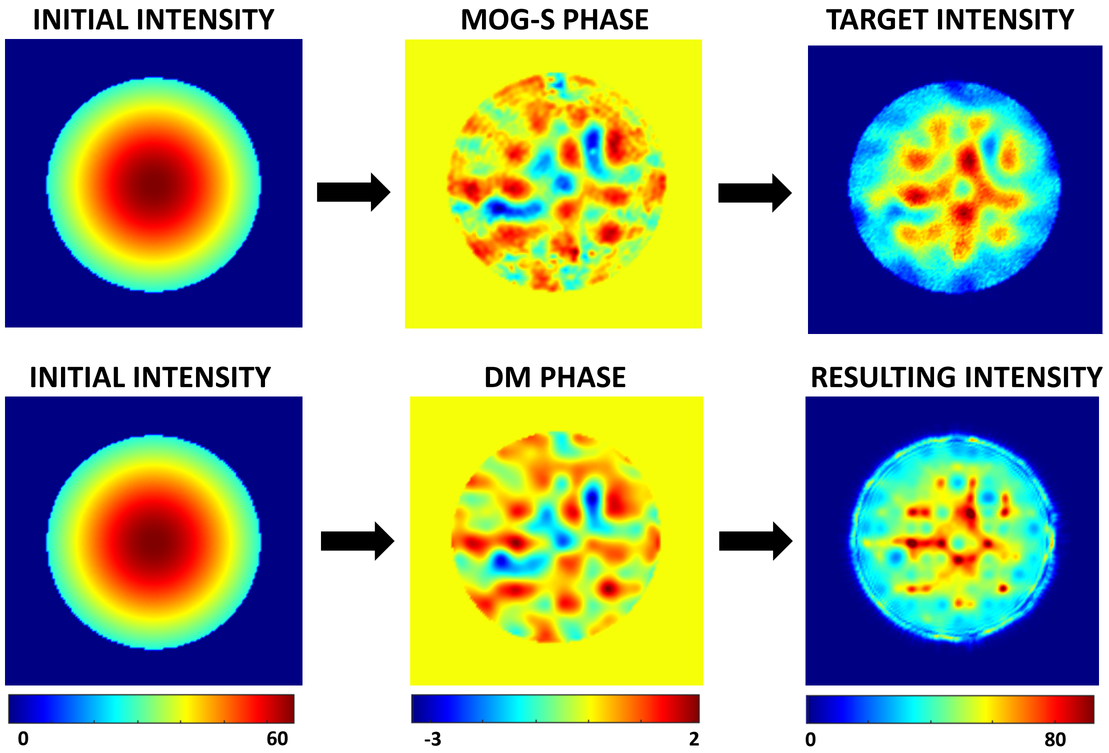
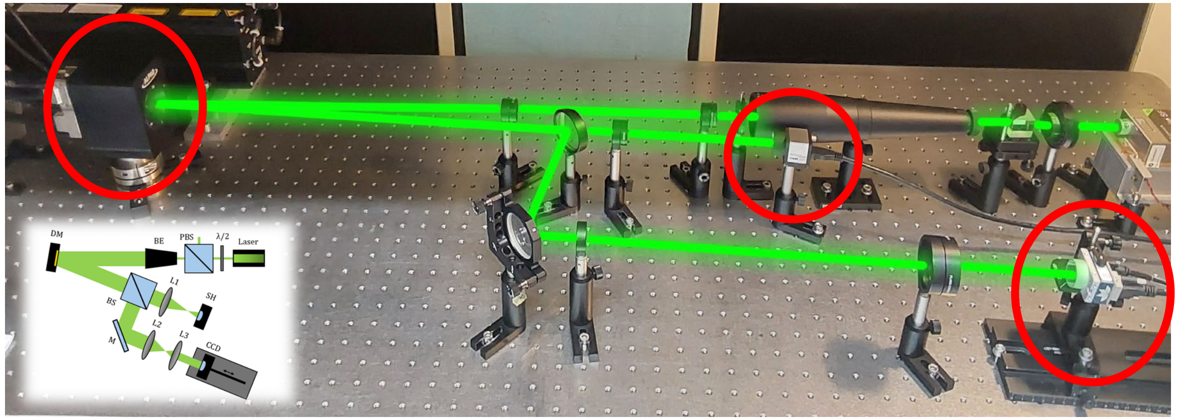


- **Experimental Setup**
  - ➢ the laser (λ = 532nm) impinges on DM
  - ➢ SH wavefront sensor in the DM image plane to control the DM-induced phase variation
  - ➢ CCD (on a translation stage) measures the correspondent intensity after propagating at distance z from DM.



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Conclusions and future plans

HEATER ARRAY FEATURES:
- Action directly on the HR surface
- No noise problem in the arm cavity
- Versatility by changing the mask
- Power dependent and limited
- Upgradable efficiency (mask size and geometry)
- Long thermal times
- New technology

DEFORMABLE MIRRORS FEATURES:
- Possibility to act on the CP out of arm cavities
- Versatility by changing code parameters
- High power operation
- Good efficiency
- Upgradable resolution
- Fast actuation times
- Well known technology

Given the diversity of effects to be corrected, both technologies are required, and it is crucial to advance research on both existing and upcoming detectors

Conclusions and future plans

HEATER ARRAY FEATURES:
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Poster #84
TDS: ET-0185A-25

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TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA
Macroarea di Scienze Matematiche, Fisiche e Naturali

ADVANCED OPTICS LAB @ TOR VERGATA FOR ET

References

Aidan F. Brooks et al. , - Point absorbers in Advanced LIGO - arXiv:2101.05828 (2021)

M. Cifaldi, Mitigation of anomalous absorptions in the Virgo core optics, Ph.D. Thesis (2023)

M. Cifaldi, L. Aiello, D. Lumaca, C. Taranto, - Adaptive Optics for Aberration Control in Einstein Telescope – doi = 10.3390/galaxies13020018 (2025)

A. Allocca, A. Chiummo, P. Ruggi, H. Yamamoto - Transient power drop in dark fringe lock acquisition during the commissioning before O3 (VIR-1047A-19)

R. Day - Simulation of use of phase camera as sensor for correcting common high order aberrations in MSRC (VIR-0389A-11)

Mehrabkhani S., Kuester M. - Optimization of phase retrieval in the Fresnel domain by the modi ed Gerchberg-Saxton algorithm, arXiv1711.01176 (2019)

C. Taranto, Upgraded optical aberration correction techniques for Advanced Virgo plus: commissioning toward O4 and mitigation of non-axisymmetric optical defects, Ph.D. Thesis (2023).

BACKUP SLIDES

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The point defects: characterization and diagnostic

Procedure steps:

- Wavefront acquisition with HWS on-axis setup
- Preparation of the HWS map (Piston, Tilt and curvature terms extraction) and identification of the mirror center in the HWS map
- Identification of the point position and deformation dimension
- Evaluation of the point OPL and coordinate time variation
- Estimation of the absorbed power
- Recovery of the corresponding thermo-elastic deformation