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AiLoV ADVANCED OPTICS LAB @ TOR VERGATA FOR ET

Preparing for thermal aberrations mitigation in ET: Wavefront Sensing and Control developments at AiLoV-ET

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Future high-power operation of *Einstein Telescope (ET)* in its *high-frequency dedicated configuration (ET-HF)*, is expected to amplify the *impact of thermally-induced optical aberrations*, posing new challenges for beam quality and interferometric stability. Building on the legacy of thermal compensation systems developed for Advanced Virgo, we are currently investigating *advanced wavefront sensing and control (WSC) concepts* aimed at addressing the needs of next-generation detectors within the *AiLoV-ET (Advanced Optics Lab @ Tor Vergata for ET) infrastructure*.

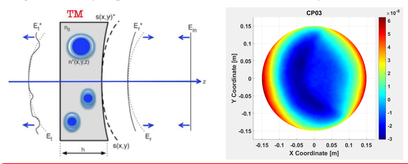
A dedicated testbench is being developed to serve as a central platform for *investigating thermal aberrations* and *validating wavefront control strategies* under realistic interferometric conditions. Around this core setup, several R&D activities are underway — including improved laser beam shaping, adaptive thermal actuation, and enhanced wavefront sensing — to support both the investigation of fundamental limitations and the development of novel compensation strategies.

This contribution will provide an overview of the WSC activities currently underway within AiLoV-ET, highlighting the experimental platforms and technologies under development to support the ambitious goals of ET-HF.

Power absorption & aberrations

Sources

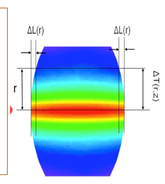
- imperfections in the production process of the mirrors (**cold defects**);
- absorption of optical power in the coatings and substrates of the optics (**dynamical effects**).



Effects

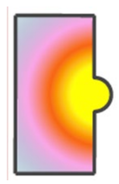
Thermal lensing

OPL distortions due to dependence of **refractive index** from temperature variation



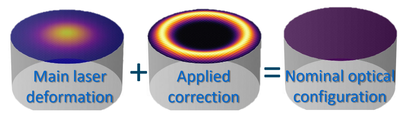
Thermo-elastic effect

Change of radius of curvature (RoC) of mirrors due a non-zero material's **thermal expansion coefficient.**



Increased circulating power will amplify the impact of ***residual optical aberrations***

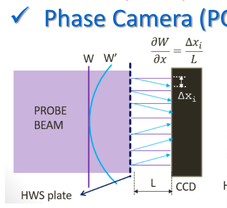
So far: AdV Thermal Compensation System (TCS)



- **Strategy**: introduce a **complementary distortion** with respect to the main laser one, restoring the nominal optical configuration.

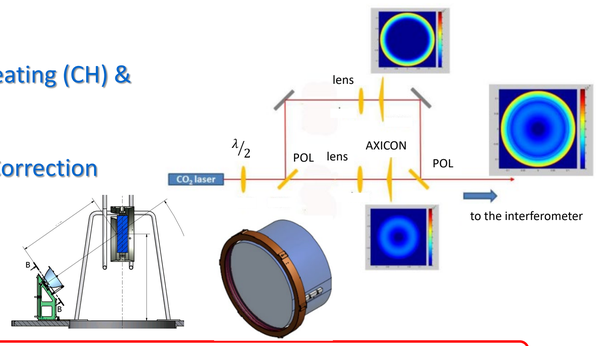
TCS sensing:

- ✓ Hartman Wavefront Sensor (HWS)
- ✓ Phase Camera (PC)



TCS actuators:

- ✓ CO_2 laser projector (50 W): central heating (CH) & double axicon system (DAS)
- ✓ Ring Heater (RH)
- ✓ Central Heating Radius of Curvature Correction (CHRoCC)



Proven to be very ***versatile*** in dealing with contexts not initially considered in the design.

Hints gathered from current experience (1)

Beyond original intent

Form experience gained with AdV

- TCS used to face **commissioning needs**:
  - ✓ CH for correction of cold transmission maps, improvement of contrast defect
  - ✓ Thermal lens due to RH serve as reference for the centre of mirrors in HWS maps
  - ✓ HWS SLED beam used as reference for detection parabolic mirror replacement…
  - ✓ …
- TCS actuators can be useful in **tackling foreseen issues**
  - ✓ RH on end mirrors could be employed to reduce the impact of parametric instabilities
  - ✓ …
- TCS methods can **help in approaching other problems**
  - ✓ Adaptive mode matching for injection of squeezed beam
  - ✓ Reduction of round-trip losses in filter cavities

Room for growth

Independency/redundancy of actuators and sensors complementary to versatility:

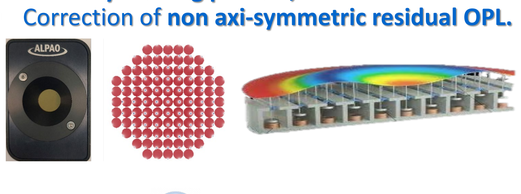
- ❑ Sensors should **disentangle accessible observations** as far as possible by design;
- ❑ Actuators should be able to **control separately the relevant DOFs** within actuation dynamics.
- ❑ **Redundancy** of control can free actuation resources → boosted versatility

Key concepts to tackle optical aberrations in future GW detectors: ***flexibility, independency and redundancy***

Advanced Wavefront Sensing and Control (WS&C) developments at AiLoV-ET

Adaptive Optics: Deformable Mirror (DM) (4)

- Imprint a phase on CO_2 beam to obtain the **desired intensity heating pattern;**
- Correction of **non axi-symmetric residual OPL.**



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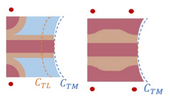
Coupled RH (11)

- RH introduces a thermal lens (C_{TL}) inside the substrate
- The C_{TL} could be compensated, placing a **second RH near the HR surface**, such that the OPL is almost constant along the thickness.



New HWS (8)

- **New sensor**(9) based on CMOS technology (Ximea):
- **New custom thermal housing** in aluminium
- The new HWS have been thoroughly characterized

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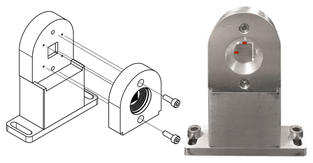
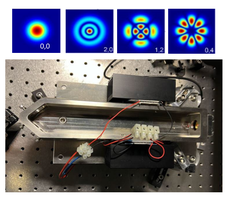
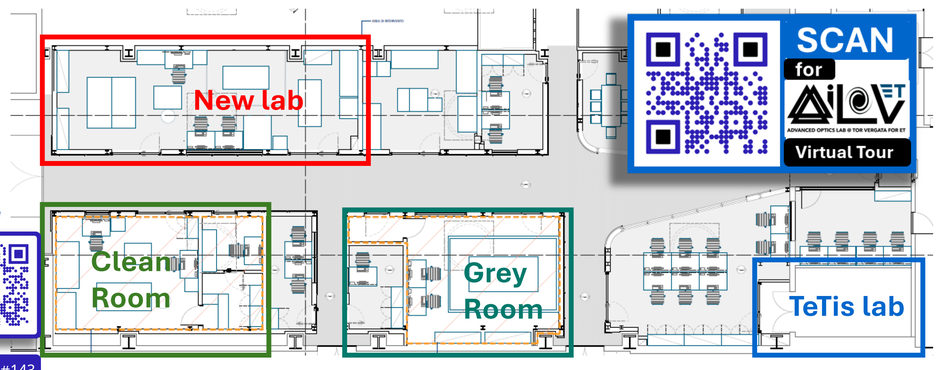


CO_2 Mode Cleaner (MC) (5,6)

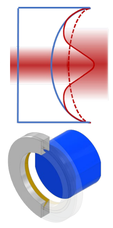
- Efficiency of DAS correction strictly related to the laser beam quality;
- TEM_{00} Gaussian VS **High Order Modes** (HOMs);
- Mode cleaner cavity for high power CO_2 laser has never been realized before.





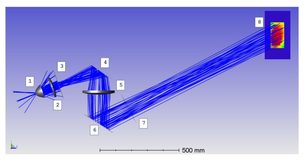
FROSTI(7)-like actuator

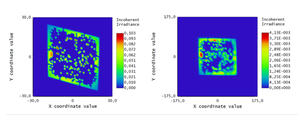
- The (spherical) curvature of the TM HR surfaces is altered by the power absorption and is compensated with the use of the RHs;
- Compensation produces a **non-spherical residual deformation**;
- The effect can be corrected by heating the HR surface with an optimal thermal radiation profile (new type of actuator).



Point Absorbers (PA) mitigation (10)

- **Highly absorbing areas** on the coatings of the core optics
- The corrective heating pattern is reproduced by a **binary mask illuminated by a thermal source**, with each hole acting as an actuator.

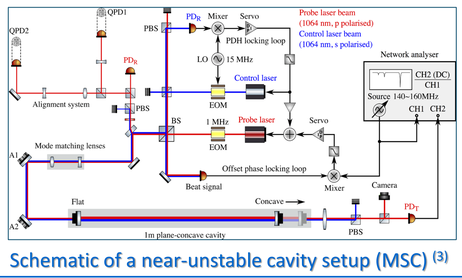




TALK #83 - ISB

Marginally Stable Cavity (MSC)

- A new facility with a marginally-stable cavity (MSC) will be hosted in the AiLoV-ET laboratory (2).
- This kind of cavity is **very sensitive to optical aberrations**: any small departure from the design parameters leads to a change in the cavity resonance conditions and in the degeneracy of its eigenmodes.
- As such, a MSC can be seen as **an "amplifier" of wavefront distortions**: new sensors and actuators will be integrated in the MSC facility.



Schematic of a near-unstable cavity setup (MSC) (3)

- ❖ **Remote control and interventions**, not to alter thermal status of the source
- ❖ **Monitoring** of the correction patterns

References

(1) M. Lorenzini, *High Power is Nothing Without Control: Tackling Thermal Aberrations in Future GW Detectors*, presentation at GRASS 2024, VIR-0754A-24

(2) L. Aiello et al., *The AiLoV-ET project: advanced optics and materials for tackling optical aberrations and thermal noise in Einstein Telescope*, presentation at 3rd ET Annual Meeting, 2024, #28

(3) H. Wang et al., Phys. Rev. D 97, 022001 (2018)

(4) C. Taranto, *Upgraded optical aberration correction techniques for advanced Virgo plus: commissioning toward O4 and mitigation of non-axi-symmetric optical defects*, PhD Thesis, 2023

(5) L. Aiello, *Development of new approaches for optical aberration control in gravitational wave interferometers*, PhD Thesis, 2019

(6) P. Giri, *Optimization of CO_2 laser-baser aberration control in Advanced Virgo +*,PhD Thesis, 2023

(7) Xuejun Fu et al, *Improving the Robustness of Next-Generation Wavefront Control: Characterization and Analysis of FROSTI Heating Profiles*, LIGO - T2400197, 2024

(8) A. Biot, *A new Hartmann Wavefront Sensor for the aberration control in Advanced Virgo Plus Phase II*, Master Thesis, 2023

(9) Developed in collaboration with Adealide University

(10) M. Cifaldi, *Mitigation of anomalous absorption in the Virgo core optics*, PhD Thesis, 2022

(11) E. Porcelli, *Study of 2 Ring Heaters thermal lensing compensation strategy for Virgo O5*, Technical Report, 2021