ET Wavefront Sensing & Control (Work Package)

Alessio Rocchi
INFN Roma Tor Vergata
ET WS&C Workpackage Co-chair
and
Technical Manager in the ET Organisation Project Office

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Source of optical aberrations

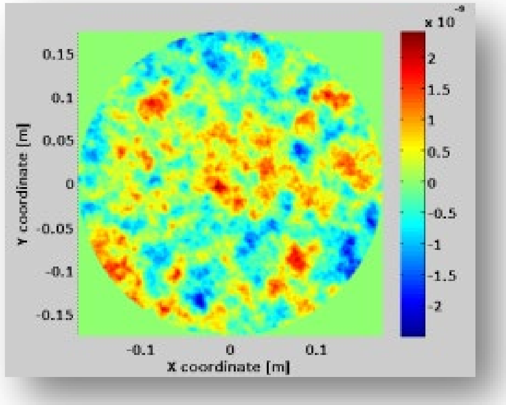
In ground-based gravitational-wave interferometric detectors, there are many kinds of optical distortions which limit both the sensitivity and the controllability of the instrument, and several parts of the detector are involved.

Two main classes:
- Generated by thermal effects;
- Intrinsic ("cold") defects due to the fabrication process.

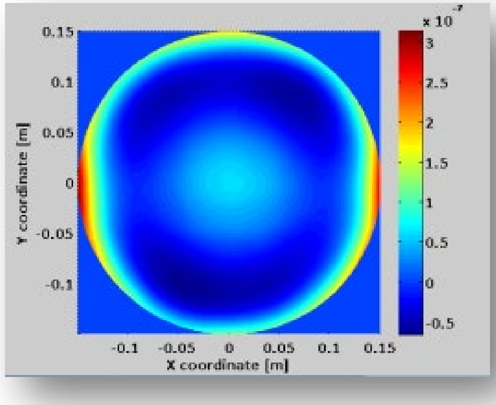
Classified also in terms of their symmetry properties.
Defects with axial symmetry:
- ☐ Uniform thermal effects;
- ☐ Contribution from ITMs refraction index non-uniformity;

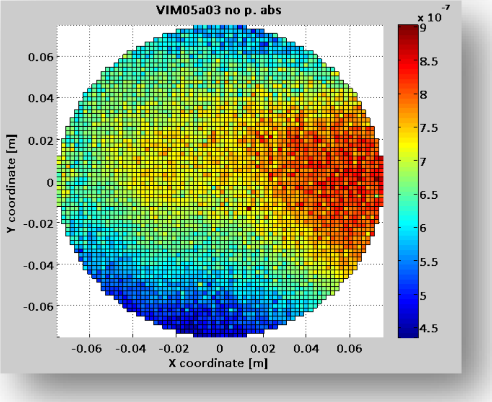
Defects without axial symmetry:
- ☐ Non uniform thermal effects;
- ☐ Contribution from ITMs refraction index non-uniformity;
- ☐ RCs optics surface figure errors.

Surface roughness map (simulated)



Substrate transmission map (measured at LMA on a aLIGO mirror)





Coating absorption map (measured at LMA on a Virgo mirror)

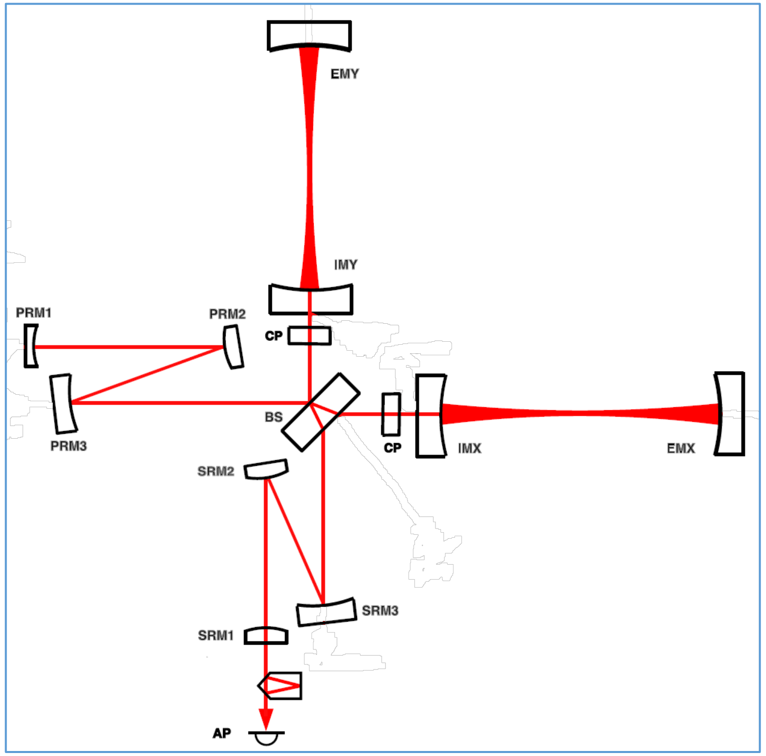
Source of optical aberrations

In ground-based gravitational-wave interferometric detectors, there are many kinds of optical distortions which limit both the sensitivity and the controllability of the instrument, and several parts of the detector are involved.

- Mirror surface figure errors: core optics and recycling cavities optics, filter cavity optics, Input Mode Cleaner optics;
- Substrate refractive index non-homogeneities: Input Test Masses (ITMs), Beam Splitter (BS) and Compensation Plates (CPs, if any);
- Distortions due to optics self-heating:
  - thermo-optic effect (thermal lensing): ITMs, BS and CPs - input Faraday isolator;
  - thermoelastic deformation of High Reflectivity surface: core optics and recycling cavities optics, IMC optics;
- Mode-matching distortions: from input optics to arm cavities; from output optics to Output Mode Cleaner (OMC); from squeezing source to filter cavity/ITF.

In the case of ET, which is made by a High-frequency room-temperature interferometer and a Low-frequency cryogenic-temperature instrument, **optical aberrations may affect the sensitivity and operability of each separate component**.

Thus, Wave-front sensing and control is needed to correct and optimize the wavefront of the electro-magnetic fields circulating in the interferometer. **For this reason, all activities concerning wavefront correction in general at all locations where this is possible have been included.**



Tasks within the scope of the WS&C

The scope of this activity is to define the optimal corrective strategy **for each aberration and each location of the detector**, based on the development of both sensing and actuation devices and schemes. Furthermore, the **development of optical simulations** to derive error signals for aberration control and to predict the behavior of the detector, evaluating figure of merits to assess the efficiency of the control, are included in the scopes of this activity

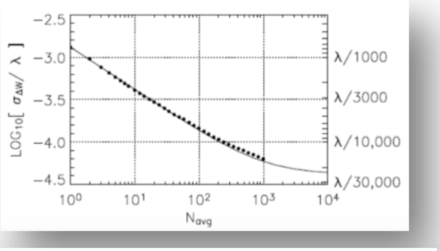
- **Simulations**: build optical simulations to translate locking requirements into requirements on aberration budget and guide design of actuators; optical simulations to derive error signals for aberration control;
- **Sensing**:
  - **Phase cameras**: definition of requirements and development of new devices;
  - **Hartmann Wavefront Sensors**: optical schemes and requirements for the device;
  - **Mode Converter telescope**: definition of requirements and development of the device;
  - **Electro-optical lens**: definition of requirements and development of the device.
- **Actuation**:
  - **Ring heaters**: definition of requirements and design of the device;
  - **Corrective pattern projectors**: definition of requirements and of the laser beam shaping technique; investigate possibility to use heaters arrays;
  - **Deformable mirrors (Thermo-mechanical actuator)**: definition of requirements and development of the device;
  - **Heaters arrays**: useful to correct residual aberrations; definition of needs and requirements and development of the device

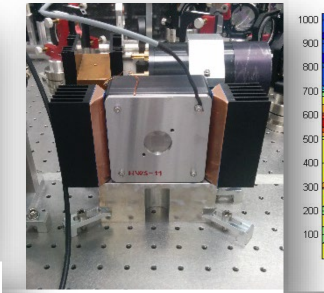
Wavefront sensing

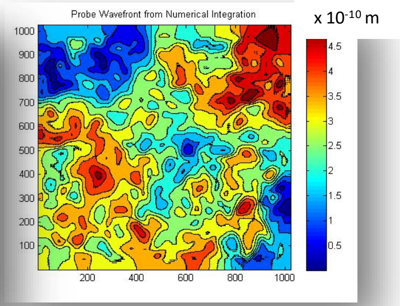
"Local" sensor:

- Hartmann Wave-front sensor;
- Uses a dedicated incoherent probe beam (from a SLED);
- On-axis sensing for thermal lensing on the input test masses;
- Off-axis measurement of the HR surface thermo-elastic deformation (change of the RoC) of all TMs;

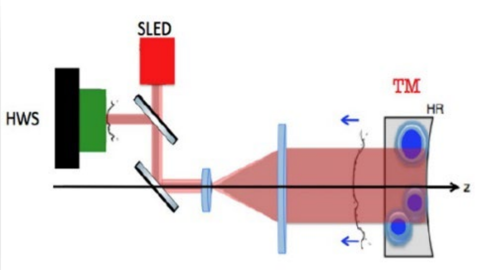
A. F. Brooks et al., Opt. Express **15** (16), (2007)

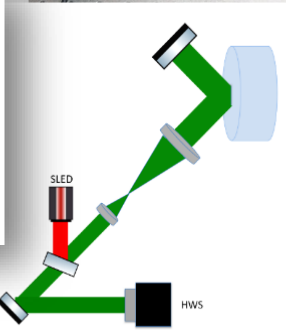


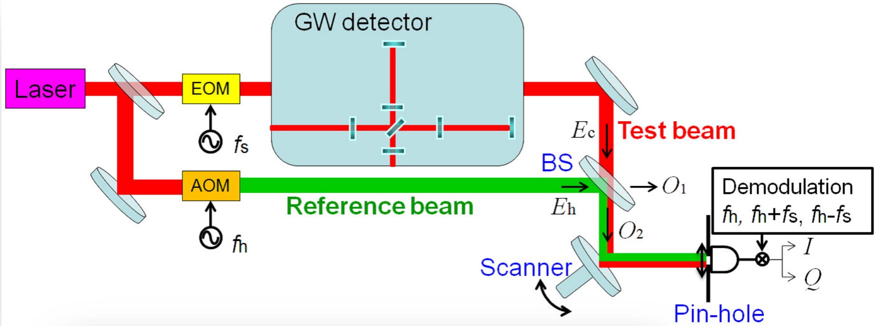


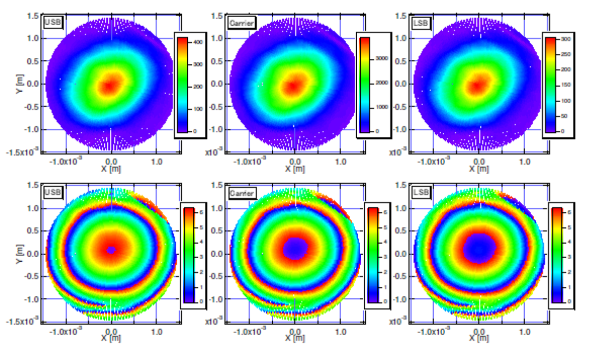


Measured wave-front averaged over 100 frames: **RMS 0.1 nm** or λ/6500 @ 650 nm







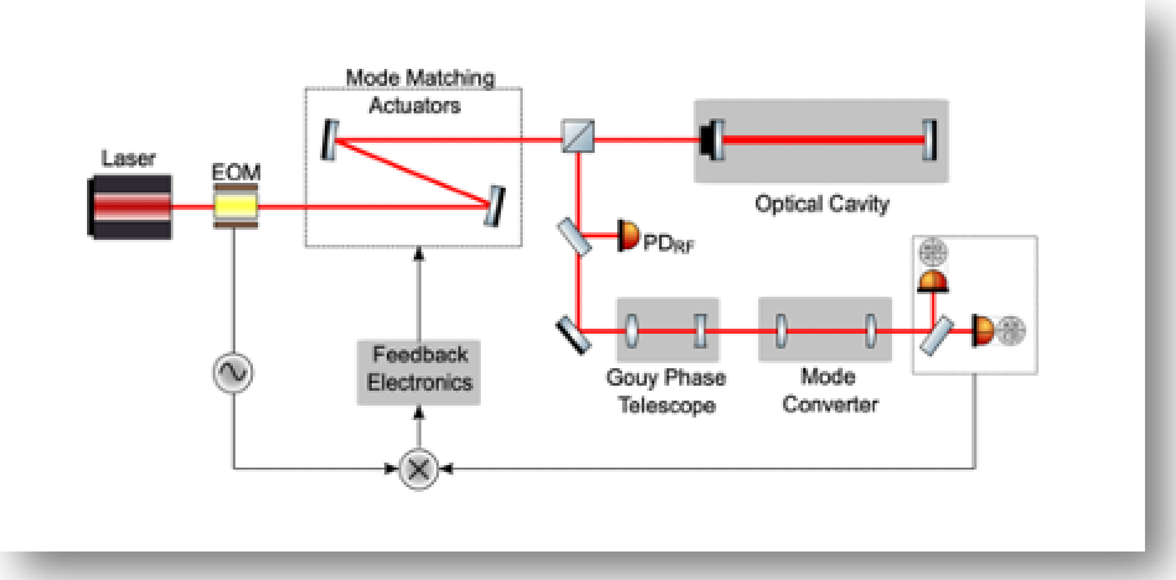


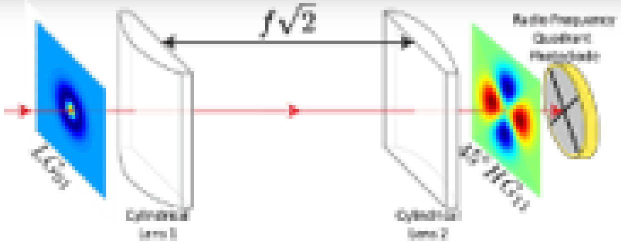
"Global" sensor:

- Phase Cameras;
- Uses a pick-off of the main ITF beam;
- Measures intensity and phase of all the EM fields (carrier and sidebands) circulating in the interferometer;
- Located at the symmetric and anti-symmetric ports;

Wavefront sensing

Mode converter telescope. The LG01 mode is transformed in a 45deg rotated HG11 mode and measures by conventional quadrant photodiodes

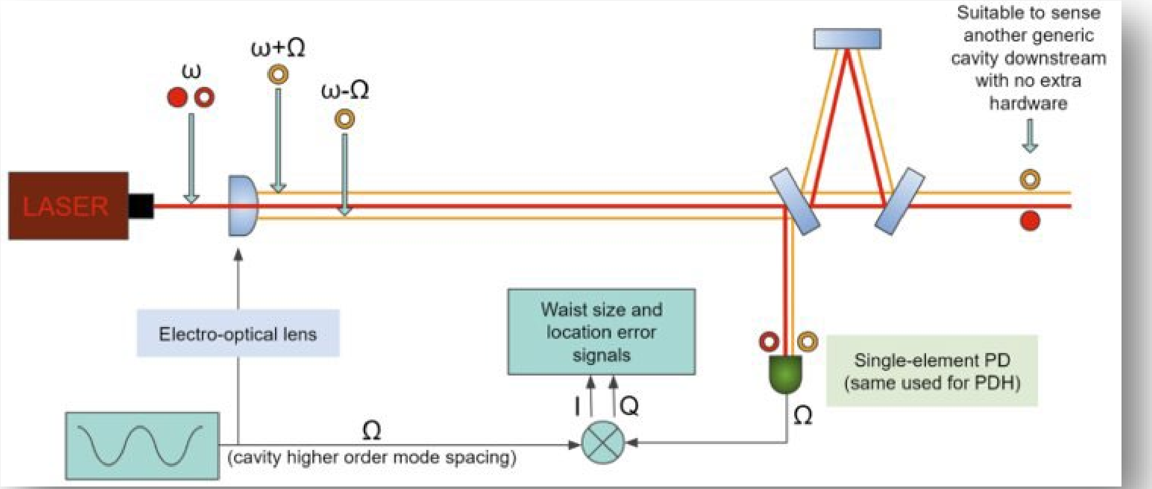




Employs an electro-optical lens (EOL, i.e. a modified EOM) to generate sidebands in the LG10 mode

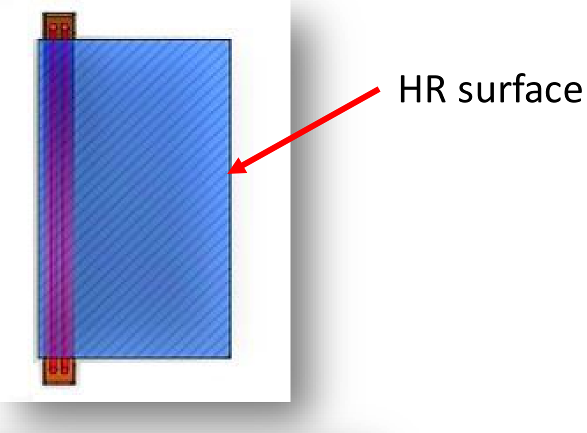
Since the mode to be sensed (mismatch) and that of the sidebands are not orthogonal, no split-photodetector is needed

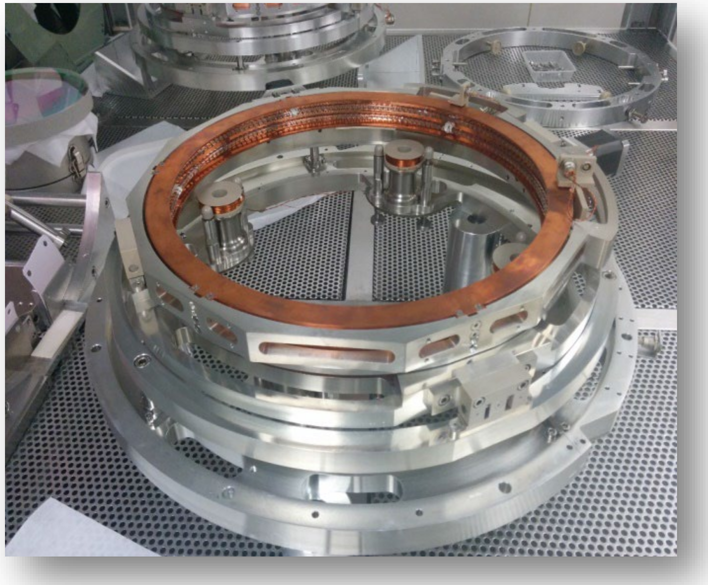
Demodulating with both quadratures the same single-element photodetector already present in reflection for PDH locking, an error signal fully describing the mismatch in beam waist size and position can be retrieved

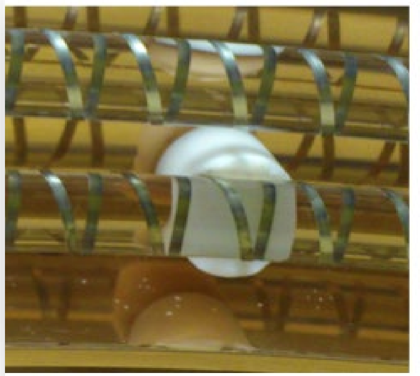


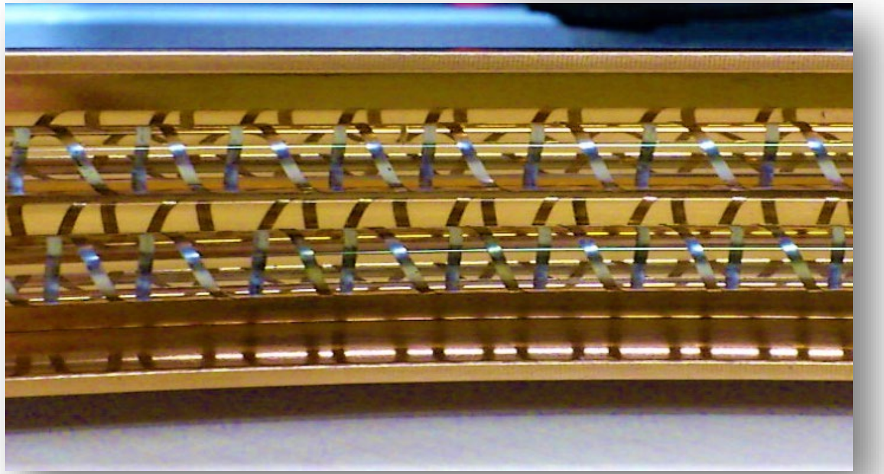
Ring Heaters

- RHs able to change the surface curvature (reducing RoC) via $\alpha \neq 0$ *and* induce a thermal lens inside the TM via $dn/dT \neq 0$
- RH used in AdV, aLIGO and GEO:
  - Ultra high vacuum compatible
  - Heating by Joule effect in NiCr coil wrapped around two glass rings
  - Internal surface of copper shields is polished for better efficiency
  - Both thermal lens and RoC change are **spherical** to high degree



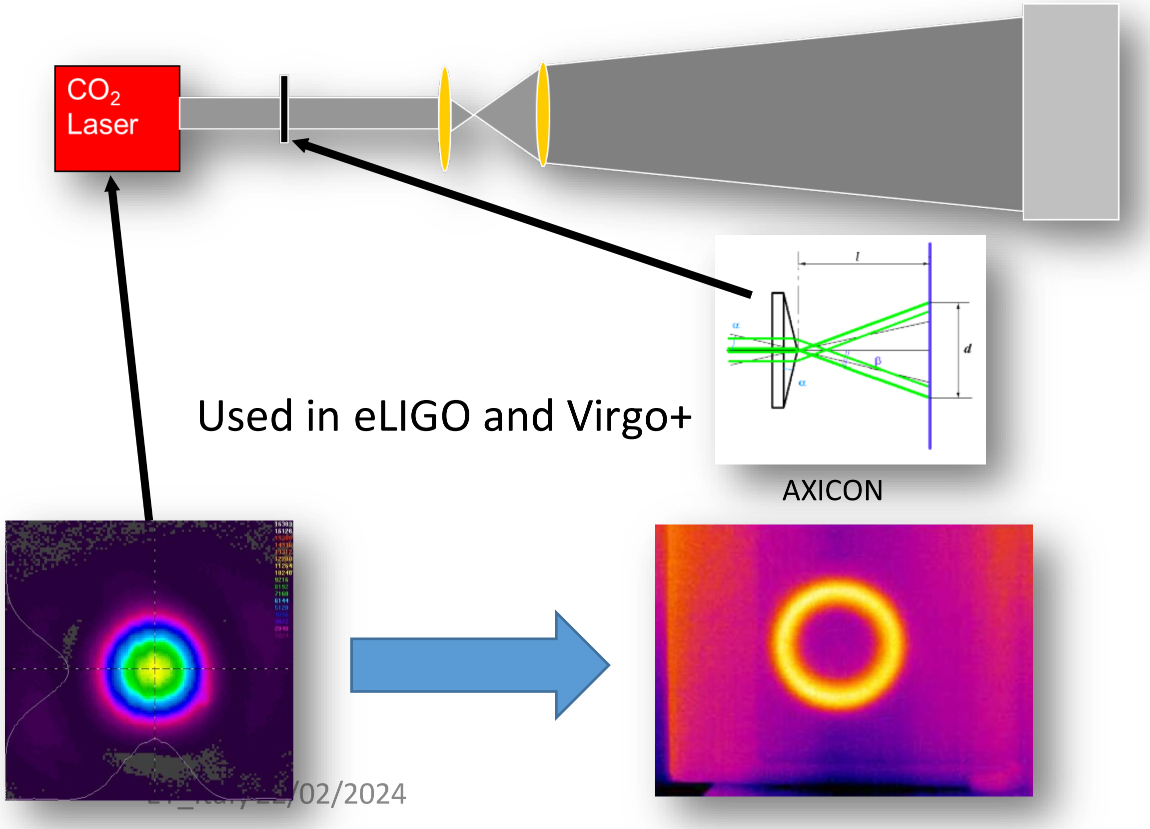




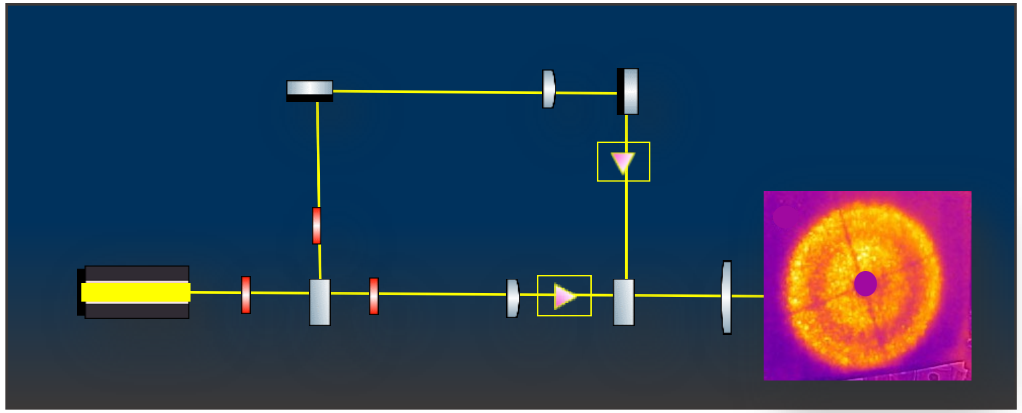


Corrective pattern projectors

- Used to produce optimized heating patterns for the minimizing aberrations with axial symmetry;
- aLIGO and AdV use CO2 lasers (optimally absorbed by SiO2) → what’s the choice for ET?



Used in eLIGO and Virgo+

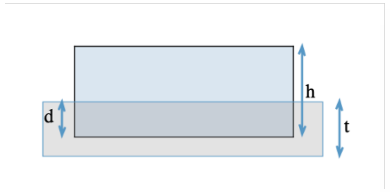


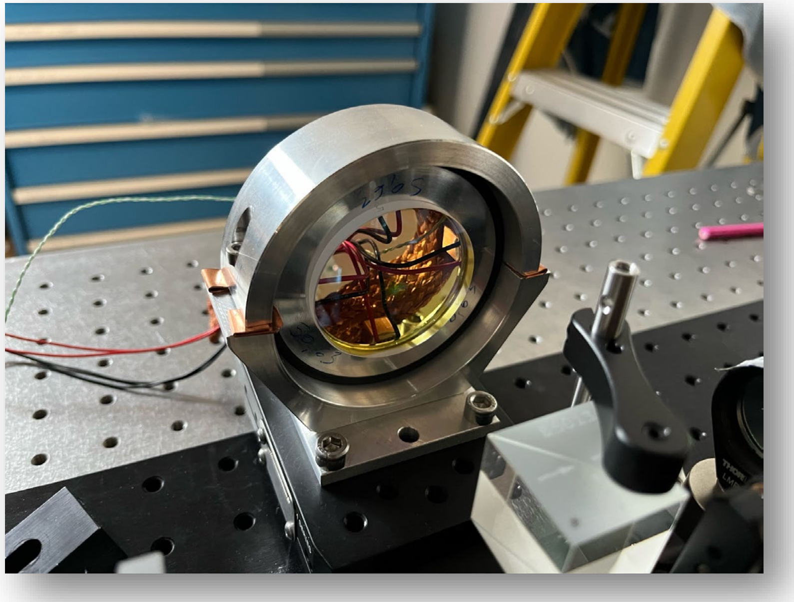
Upgraded solution for Advanced Virgo (more stringent requirements): combine two axicons (**Double Axicon System**), capability of modulating rings dimensions by changing distances between lenses and axicons and modulate power in each ring

Deformable mirrors

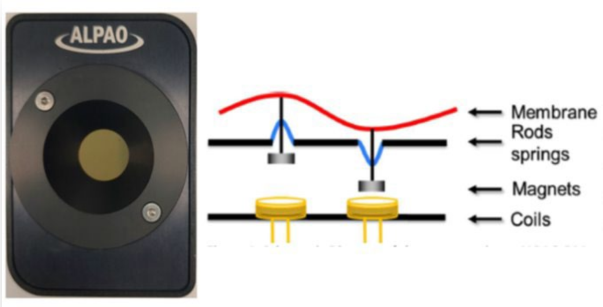
- First option: apply phase correction for direct wave-front compensation (as in astronomy)

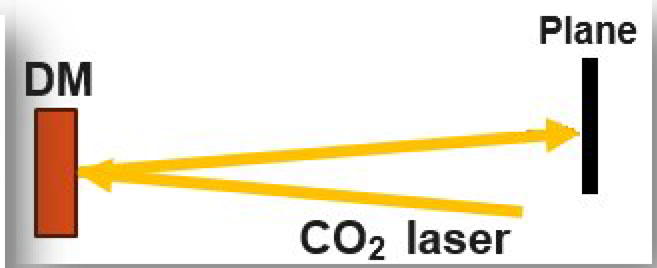
The pressfit mirror is a thermally-actuated optic based on the mechanical compression process of the optic within an aluminum ring. The larger thermal expansion coefficient of the aluminum allows the compression of the optics changing its curvature

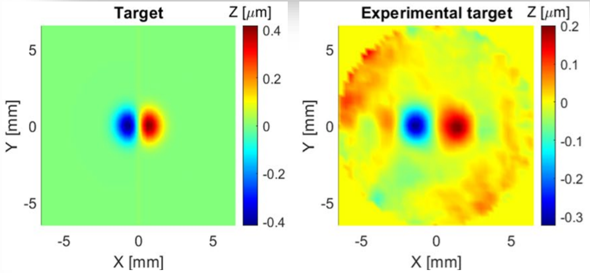




- The other option: apply phase modulation to the wavefront of an incoming CO2 Gaussian beam and convert the beam intensity pattern into the desired one holographically





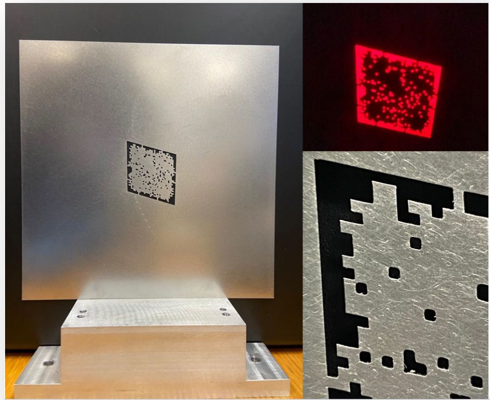


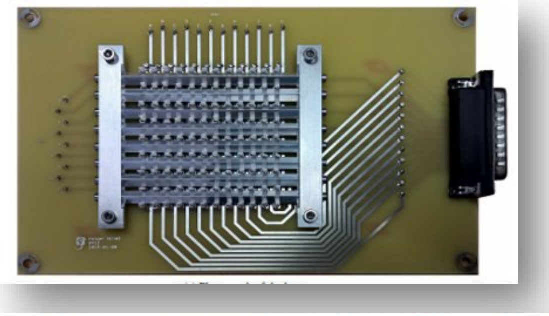
C. Taranto et al., Nuovo Cim. C, 45, 5, 155 (2022)

These devices are included in the next round of upgrades for AdV

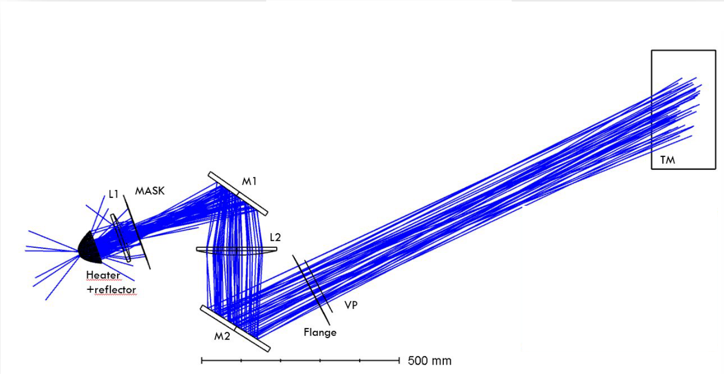
Heaters' arrays

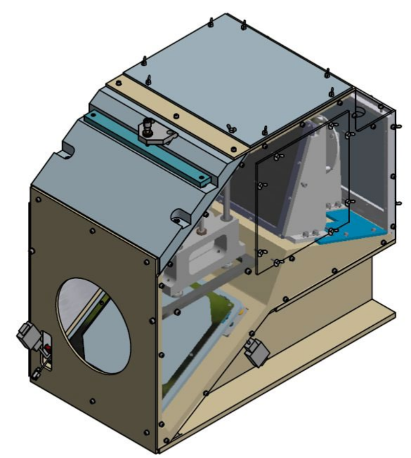
- For applications where intensity fluctuations may introduce displacement noise in the detector, heaters' arrays exploit the filtering capabilities of heating elements, combining the flexibility of a deformable mirror
- Developed and optimized within GEO and Virgo communities.





When dynamic change of heating pattern is not required, it can be reproduced through a binary mask illuminated by a single thermal source. Each hole in the mask will act as a single actuator.

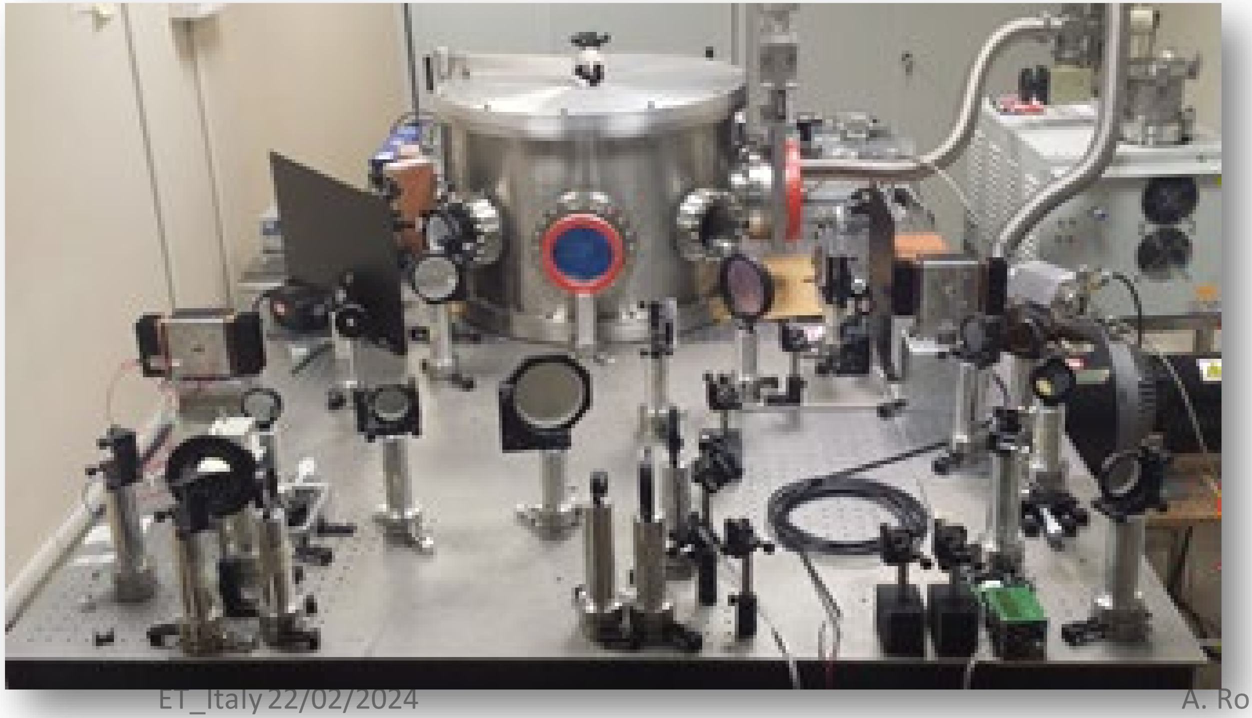


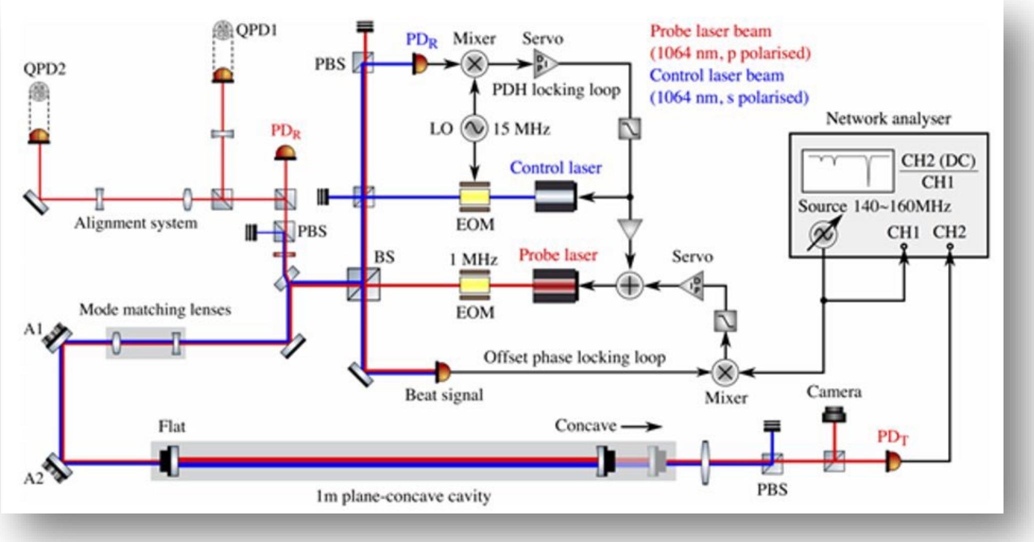


ETIC related activities

ADVANCED OPTICS LAB @ TOR VERGATA FOR ET

- **TeTis @ Tor Vergata**: a facility for testing and validating technologies for aberration control. The facility, currently hosting a scaled down Advanced Virgo test mass and CP, is equipped with two sensing lines (based on the Hartmann wavefront sensor), CO_2 laser actuation paths and a RH.
- Synergy with INFN funding to complement the facility with an optical cavity, in order to study, in a controlled environment, the effect of aberrations on error signals for longitudinal and angular control.





Conclusions

- Workpackage and technical solutions built on long-standing experience on existing GW detectors (AdV, aLIGO)
  - Participating groups know-how and expertise widely recognized at international level in the community

- Main activities in the last months: PBS and parameters tables

- Main open points:
  - Missing requirements from interferometer control
  - What wavelength for the LF corrective pattern projector?
  - How to tune the RoCs of the LF arm cavities mirrors?