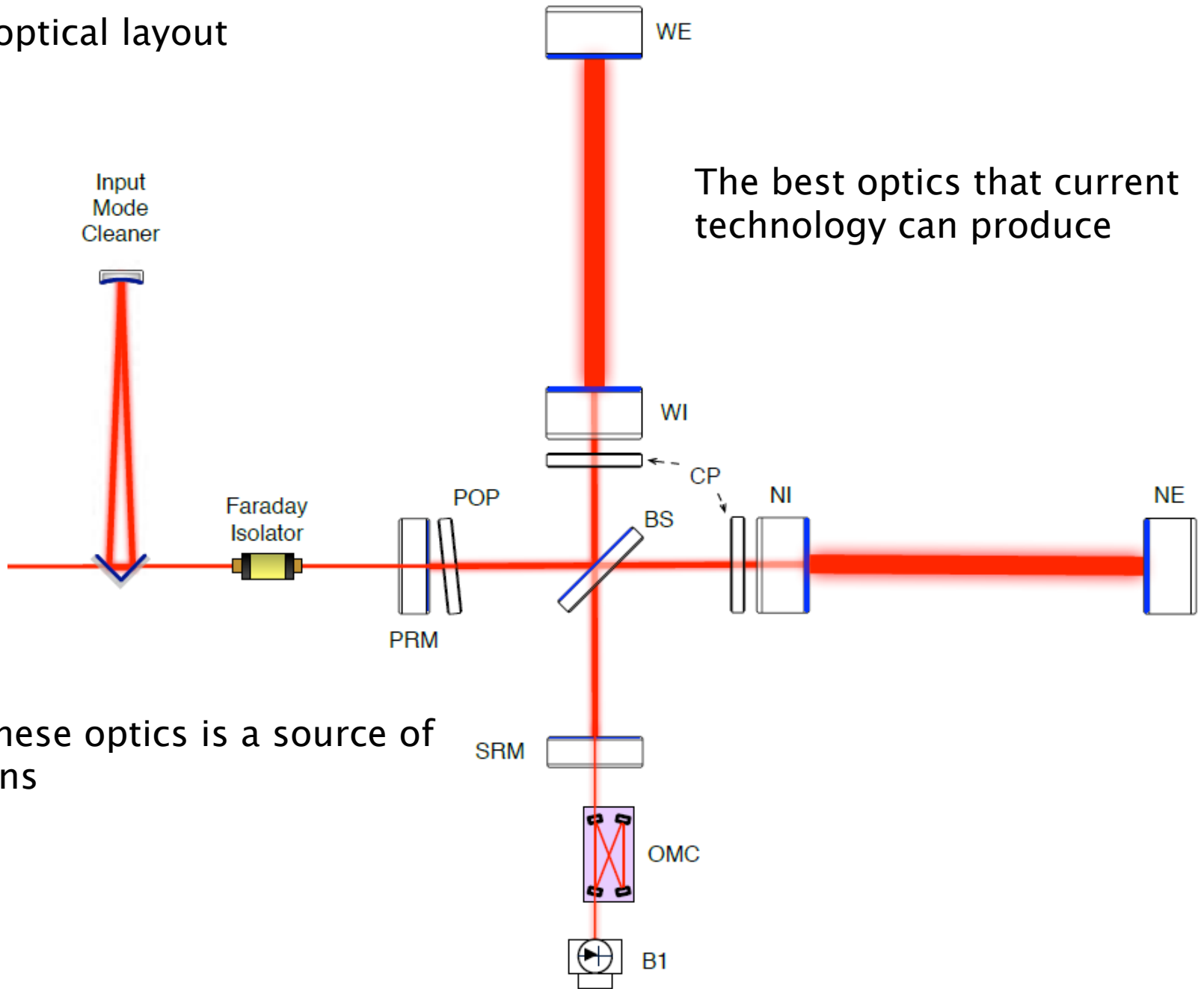


Adaptive optical systems for next generation interferometric detectors

Topics in Astroparticle and Underground Physics
Torino 7–11 September 2015

Alessio Rocchi, INFN Tor Vergata
On behalf of the TCS working group

AdVirgo optical layout



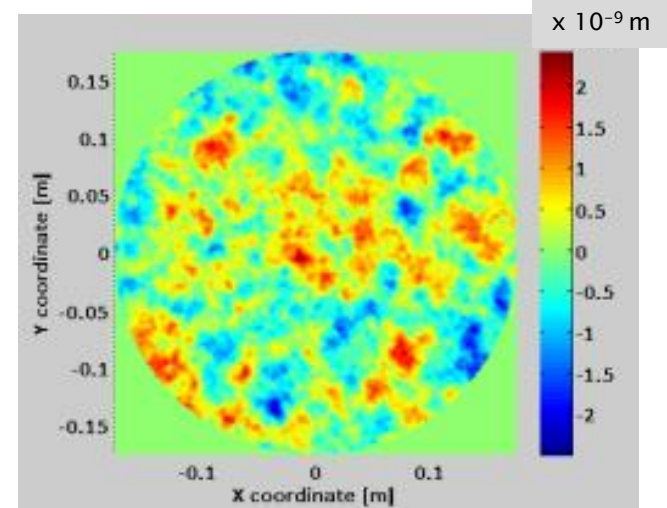
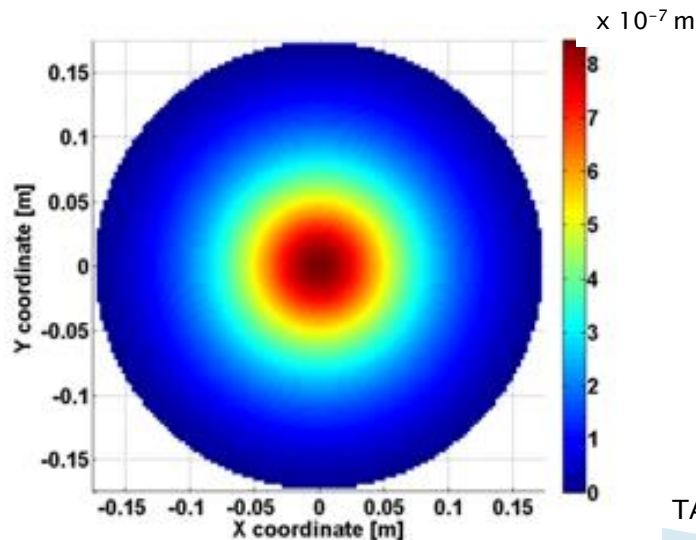
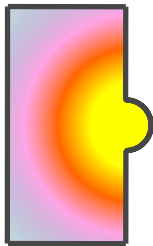
Sources of optical aberrations

Test mass fabrication process (“Cold defects”)

- ▶ Non-uniformity of the substrate transmission map;
- ▶ Mirror surface figure errors.

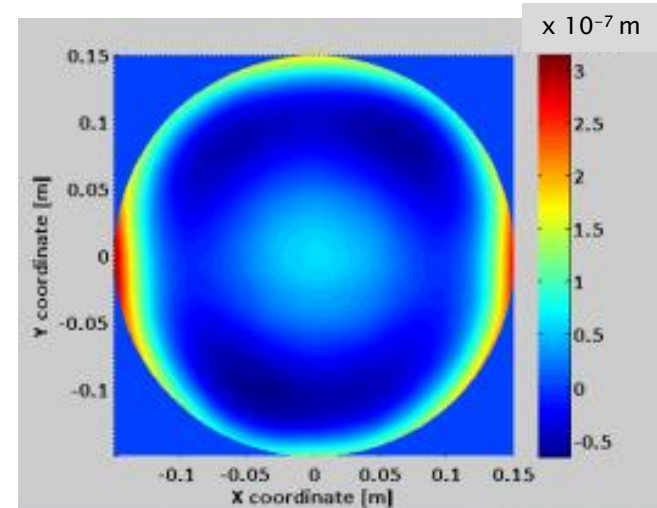
Thermal effects

- ▶ A tiny fraction ($O(\text{ppb})$) of the power circulating in the interferometer is absorbed and converted into heat;
- ▶ Mirror’s temperature increases;
- ▶ Mirror deforms (thermo-elastic deformation);
- ▶ Refraction index depends on temperature;
- ▶ Non-uniform optical path through the optic.

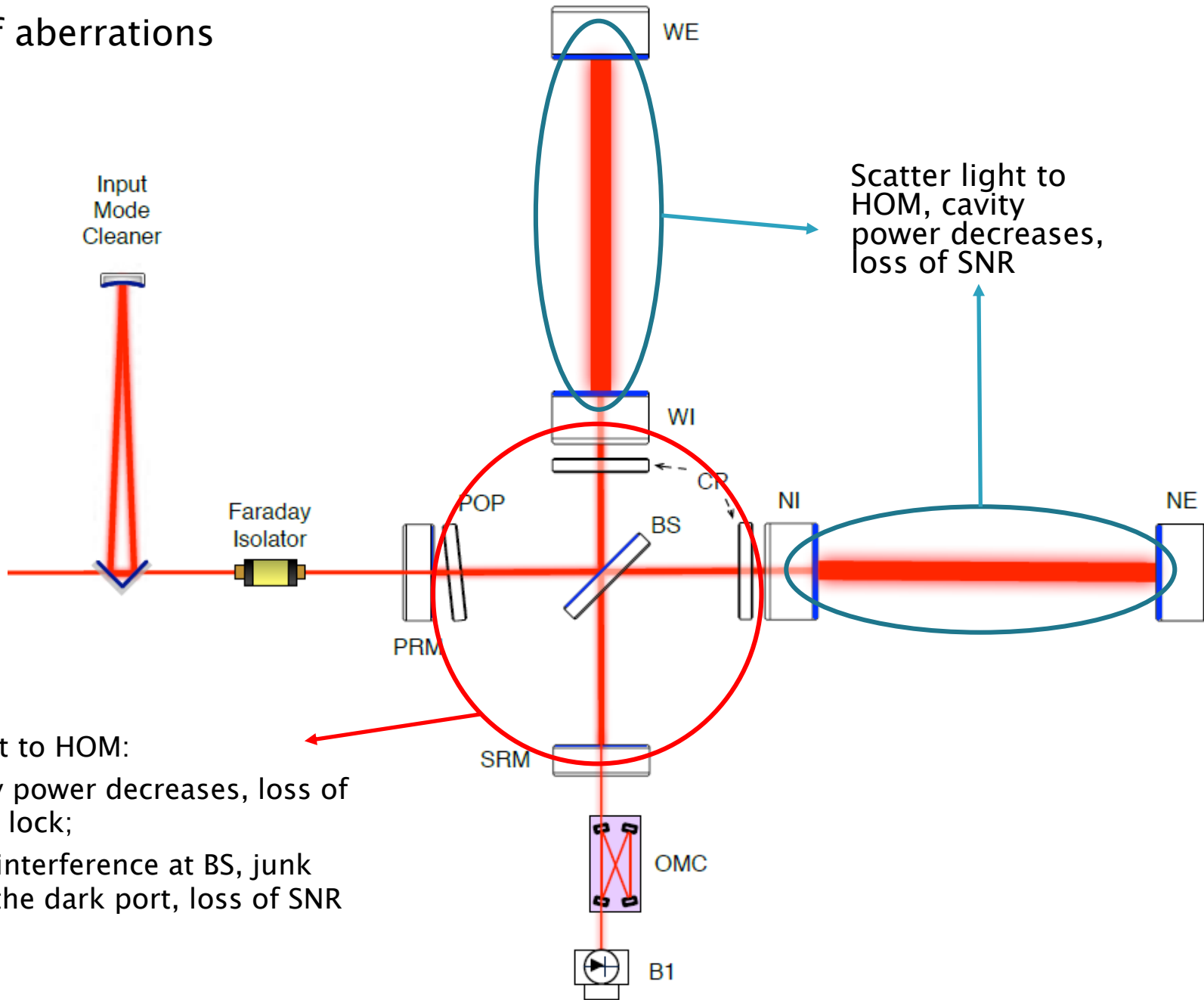


Surface roughness map (simulated)

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



Effects of aberrations

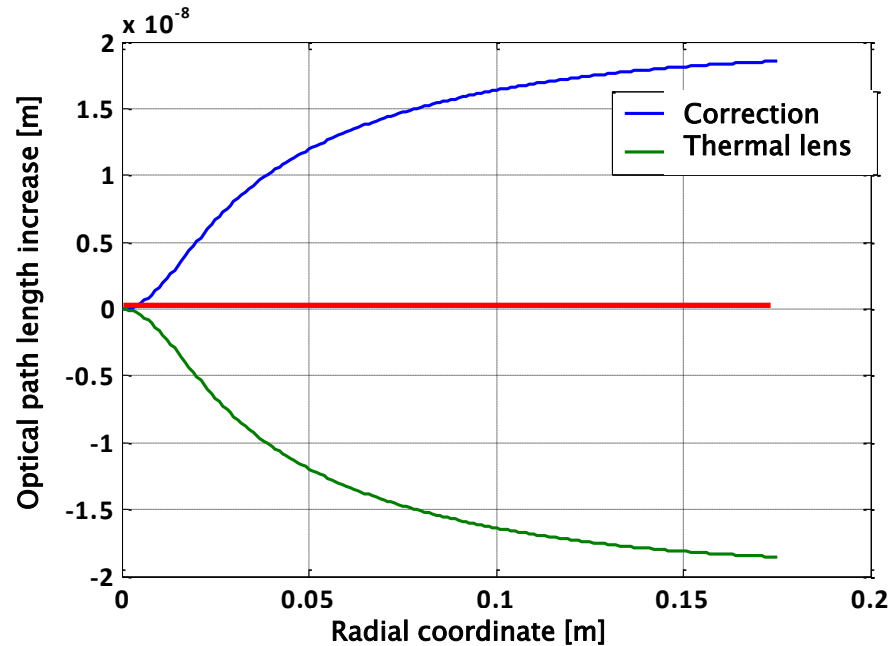


Scatter light to HOM:

- ▶ SB cavity power decreases, loss of SNR and lock;
- ▶ Worsen interference at BS, junk light at the dark port, loss of SNR

General guidelines

- ▶ Somehow we must induce in the optics an aberration equal but opposite to the defects;



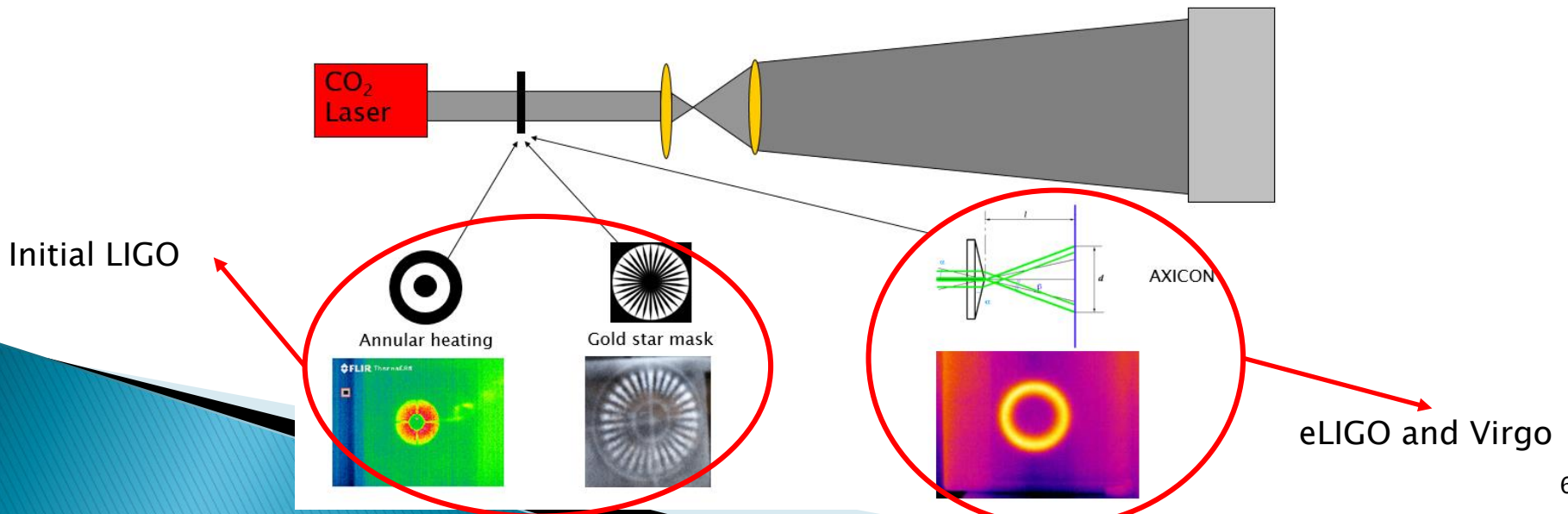
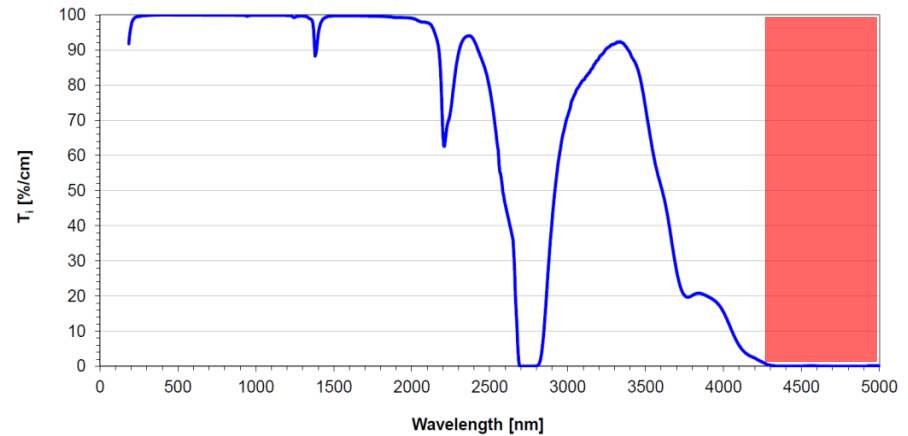
- ▶ “Cold defects” are time independent, but...
- ▶ ...the strength of the thermal lens will change with time: different ITF operating conditions, change in the absorption levels with time;
- ▶ We must use an adaptive (flexible) system in order to be able to change at will the strength and shape of the corrective lens;
- ▶ Do we have to flatten the OPL over the whole size of the mirror? → NO, only where there is the ITF beam! That is approximately 1.5 times the size of the beam on the TMs.

We can think of heating the mirrors at specific locations, to induce a “corrective” thermal lens (exploit thermo-optic effect).

Since the mirrors are our free-fall test masses, we cannot think of gluing a heater on them.

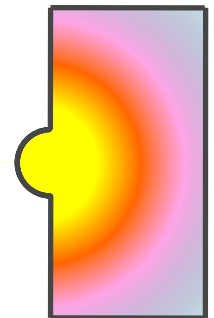
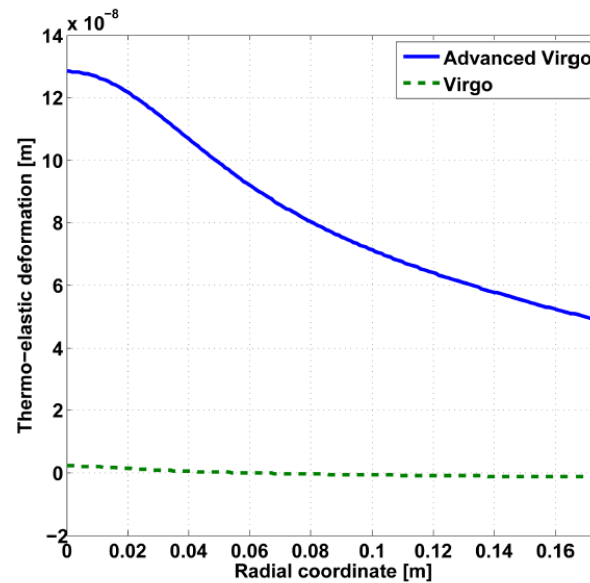
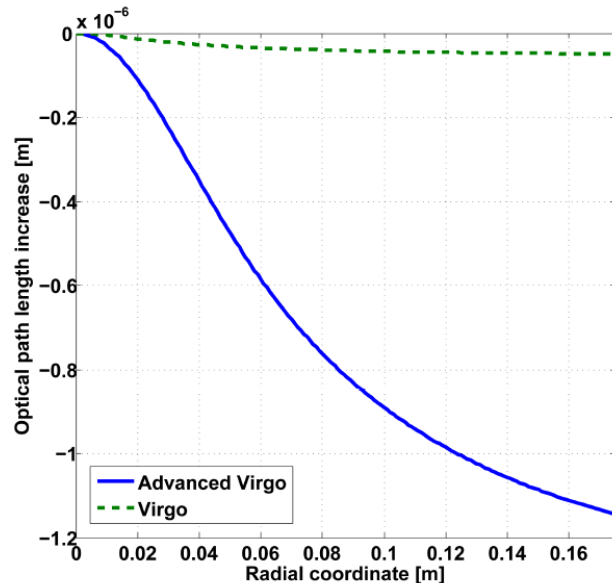
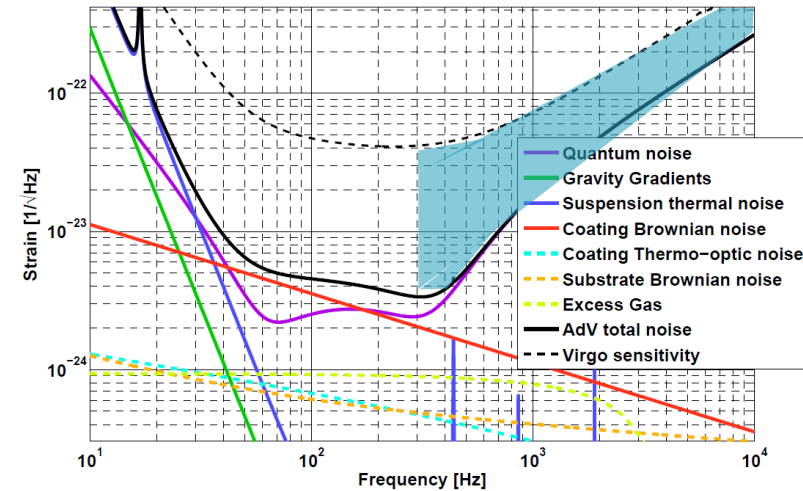
The only “touchless” way to heat the mirror is by shining it with a radiation that is completely absorbed ($> 5\mu\text{m}$ for fused silica).

LIGO and Virgo \rightarrow use of CO_2 ($\lambda=10.6\ \mu\text{m}$) lasers to heat the peripheral of the input test masses: this wavelength is all absorbed within a thin layer of SiO_2

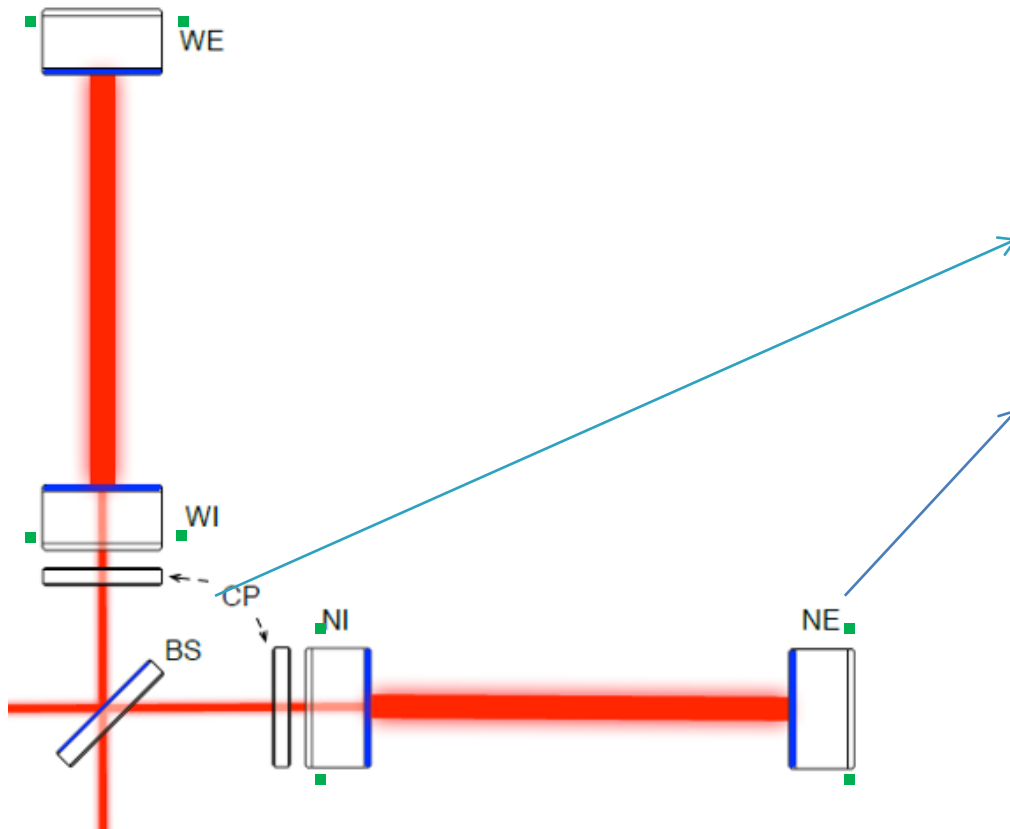


Thermal effects in advanced detectors

- ▶ Advanced detectors aim to improving the sensitivity by a factor of ten at all frequencies; also where the shot noise is limiting;
- ▶ Thus, there will be much more power circulating in the arm cavities (from 20 kW to 700 kW);
- ▶ Amplitude of the thermal lensing increases by more than one order of magnitude;
- ▶ One more effect becomes relevant: thermo-elastic deformation will change (increase) the RoC in both ITMs and ETMs, affects the FP cavity.



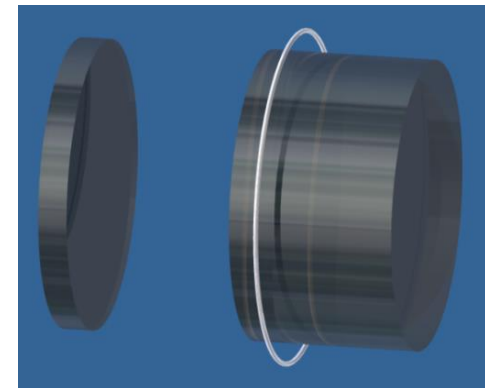
TCS in Advanced detectors



Power absorbed by TMs is about 0.5W, wrt ~20mW in initial detectors

Compensation plates shined with CO₂ laser will correct thermal effects in the RCs

Ring heaters will compensate HR surface deformations



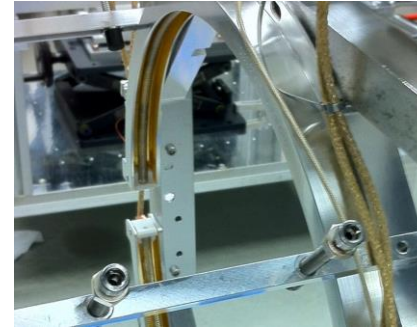
Green dots: heating rings

This set up allows to control independently the thermal lensing and the ROCs (JPS 363, 012016, 2012)

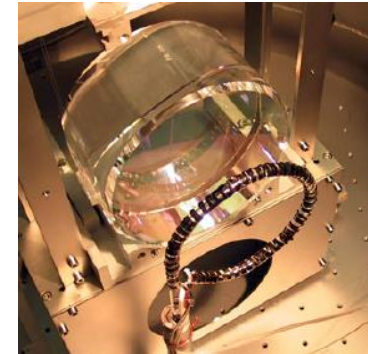
TMs ROC tuning

- Correction of the thermo-elastic deformation of the TMs is accomplished with RHs:
 - The RH bends the whole optic, in the opposite direction as the self-heating of the TM \rightarrow ROC decreases;
 - Can apply correction if TM ROC does not meet the specifications and must be decreased;
 - On the ITMs, the RH also provides some correction of the thermal lensing.
- In case some optic does not meet the requirements and ROC need to be increased, a solution can be the Central Heating RoC Correction (CHRoCC):
 - Central heating increases the ROC by changing the profile of the HR surface;
 - Heat pattern from infrared source projected on the TM;
 - Installed on Virgo ETMs (CQG 30, 055017, 2013).

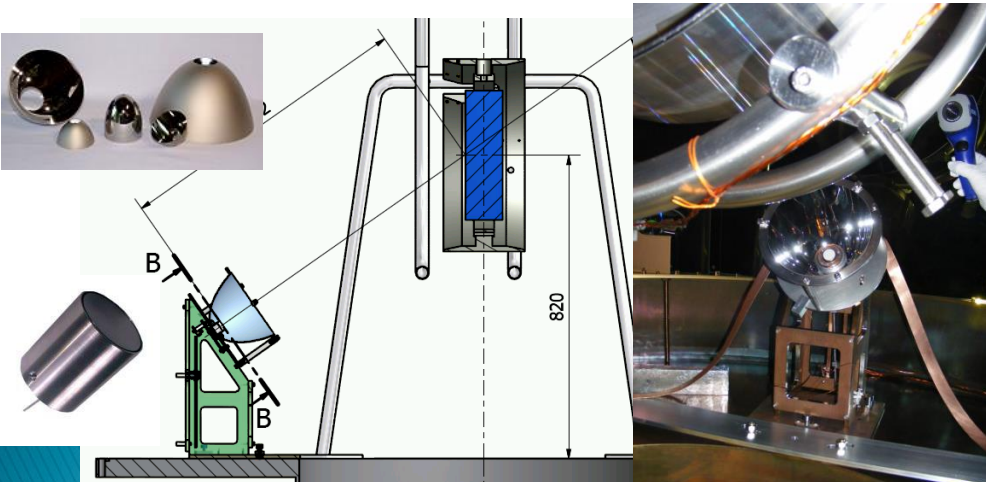
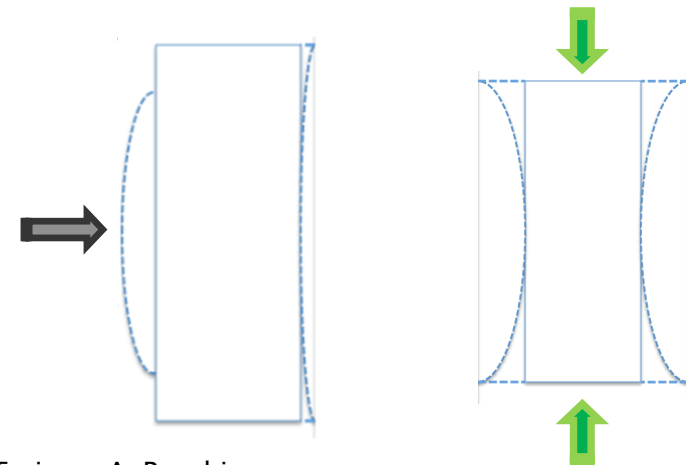
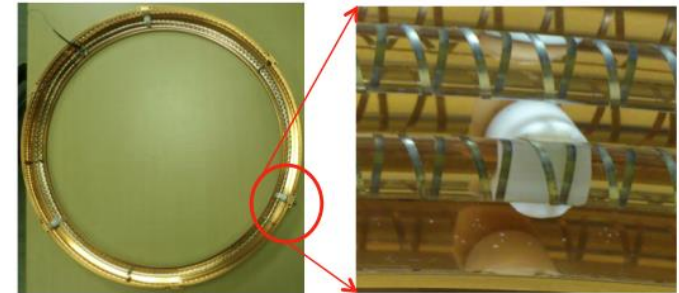
aLIGO



GEO



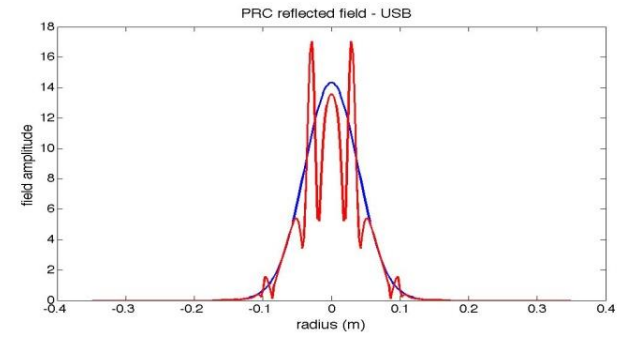
AdVirgo



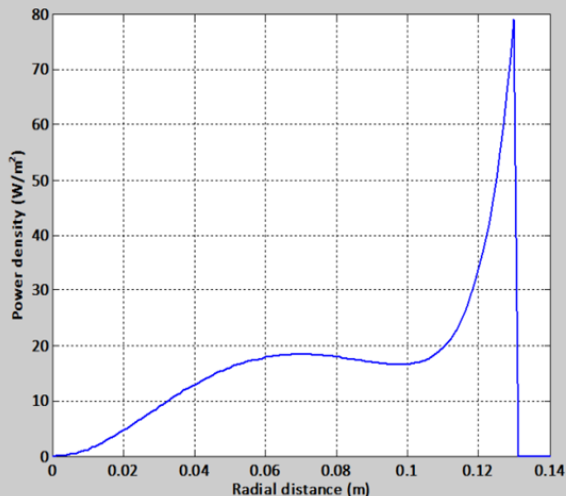
Heating pattern optimization

- The heating profile must be much more precise than in initial detectors
 - Size of the beam on ITMs become larger (from 2 cm to 5 cm);
 - Virgo-like system is not enough
 - Too high content of higher order modes in RF sidebands
- Necessity to optimize the CP heating pattern
 - Linear iterative optimization process based on FEM developed, to take into account radiative coupling btw TM and CP and the presence of the RH. Uses the OPL increase as error signal.

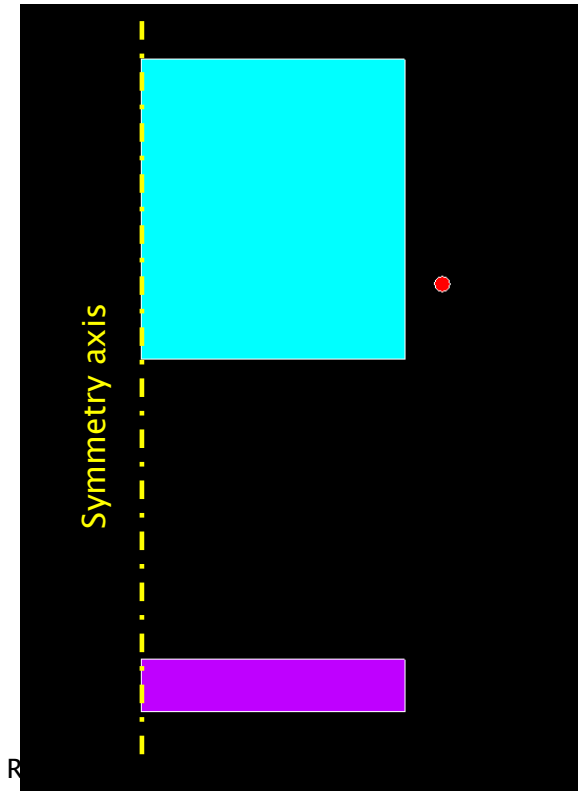
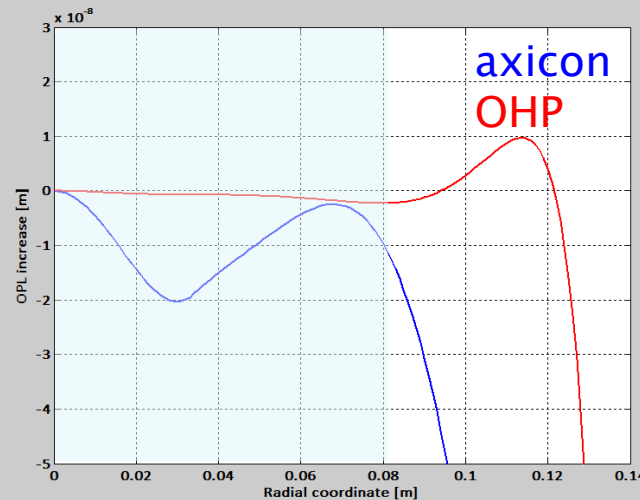
$$HPath(n + 1) = HPath(n) + K_b \cdot \Delta OPL(n)$$



Optimal heating pattern

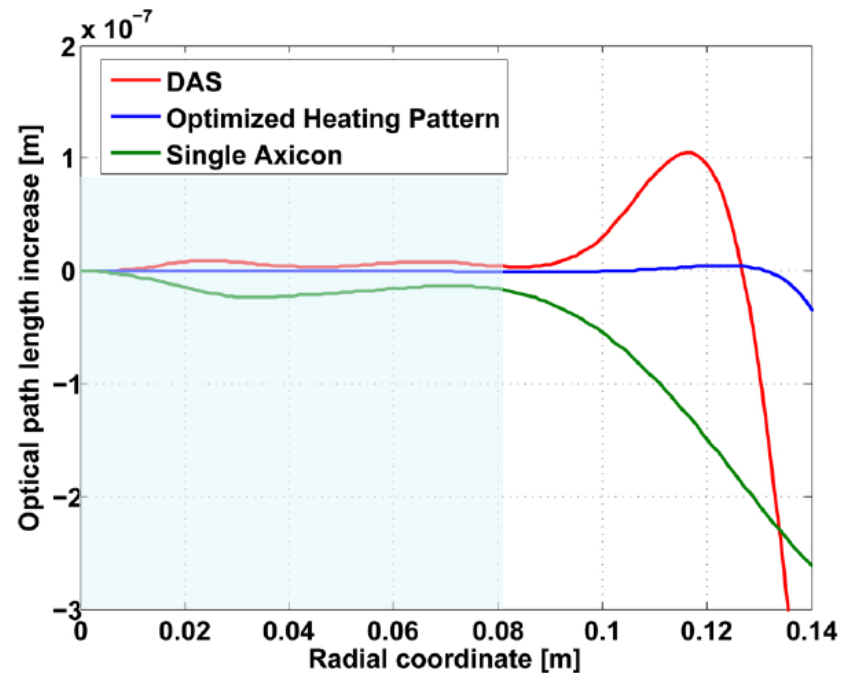
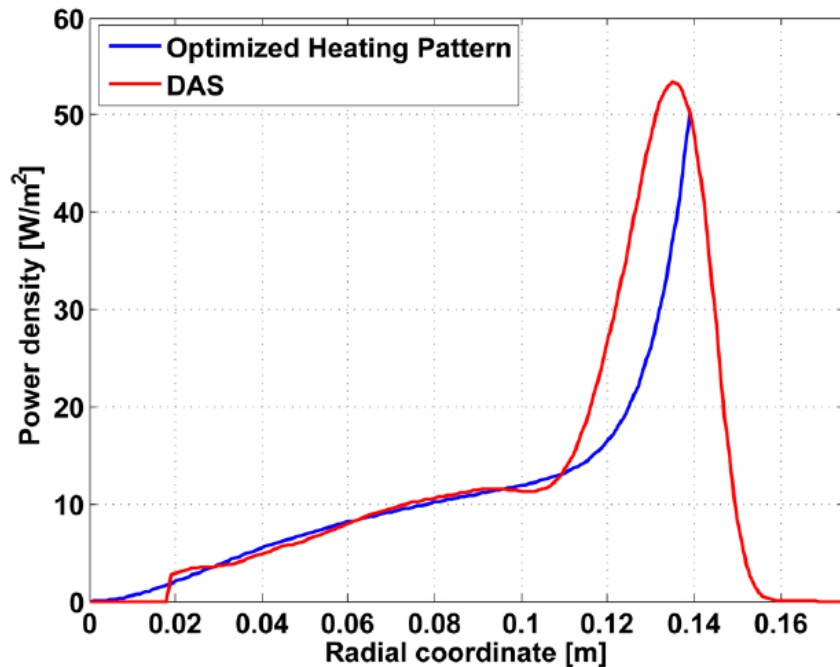
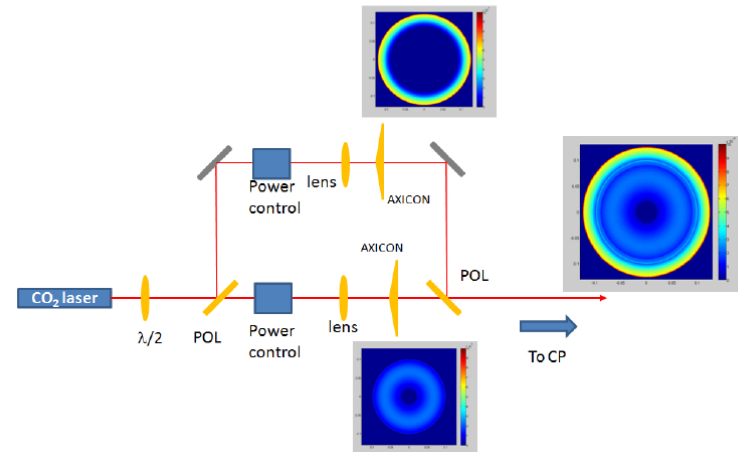


Resulting Optical Path Length



Heating pattern generation: DAS

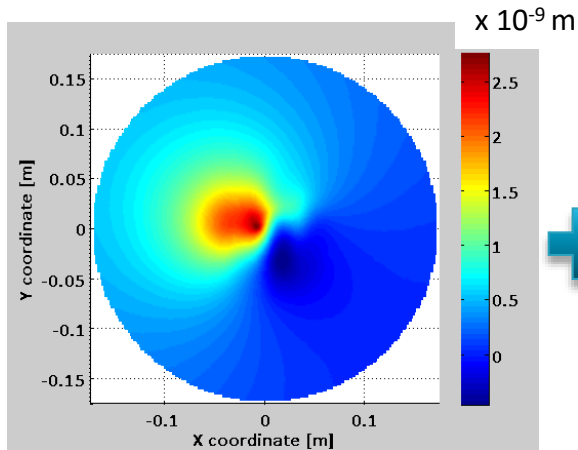
Solution using known technology: modulate rings dimensions by changing distances between lenses and axicons and modulate power in each ring (Double Axicon System)



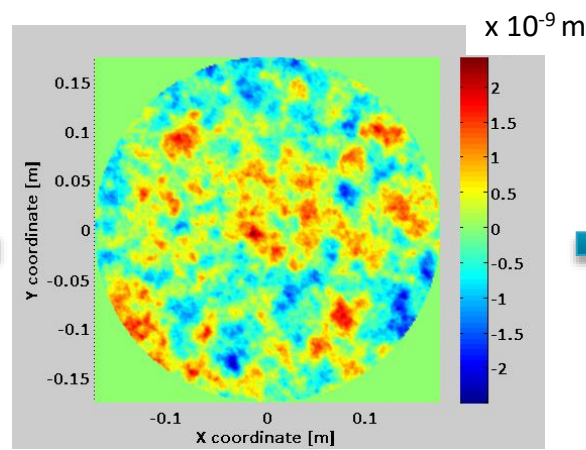
Correction of non-symmetric defects

Take all sources of non-symmetric defects (non-uniform absorptions, surface figure errors, substrate inhomogeneity).

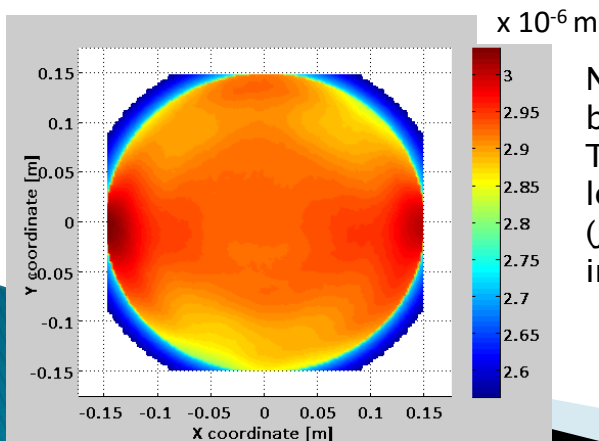
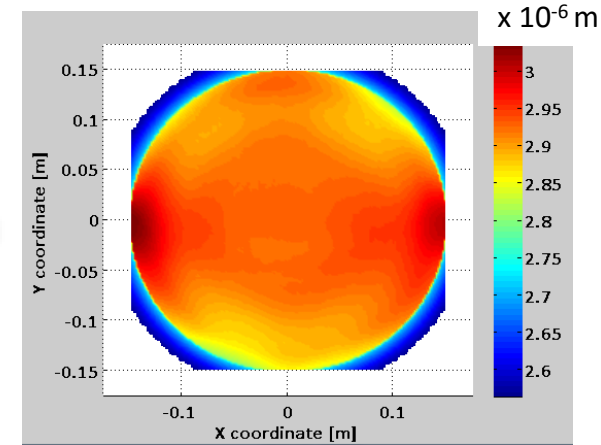
OPL due to absorption non-uniformity



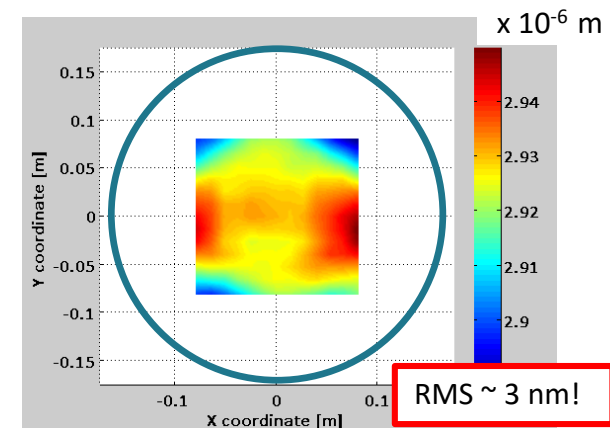
Simulated mirror map



OPL due to substrate inhomogeneity

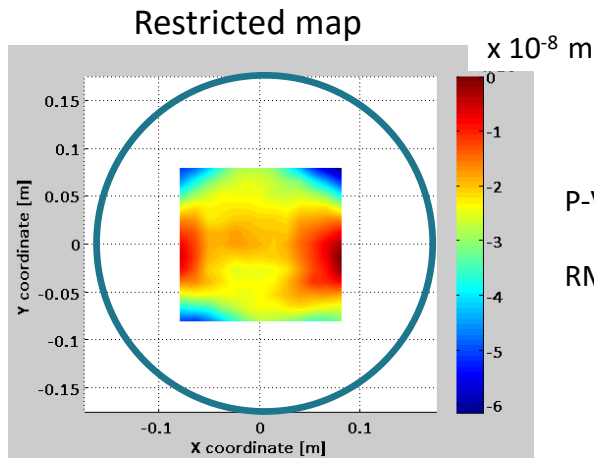


No need to correct where there is no ITF beam there.
The RMS of the residual optical path length increase must be kept below **2 nm**.
(J. Degallaix in VIR-0365A-11 and R. Day in VIR-0389A-11)

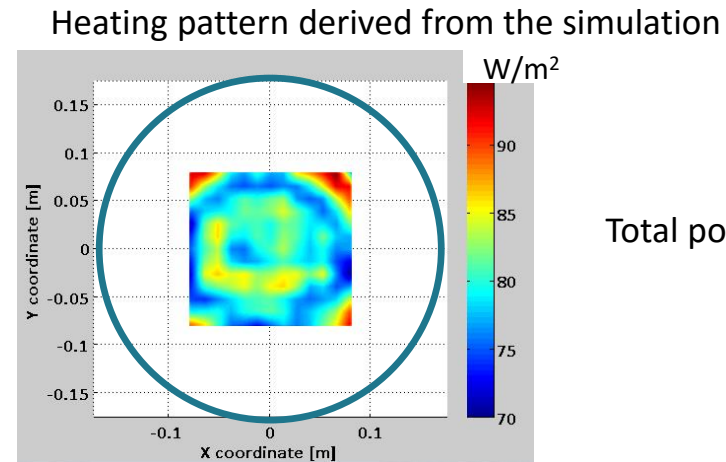


What heating pattern?

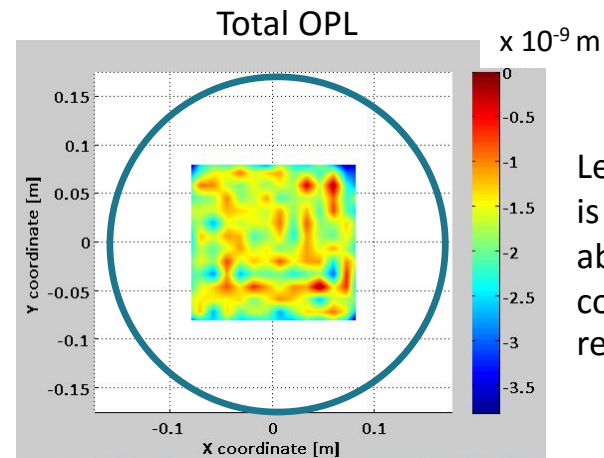
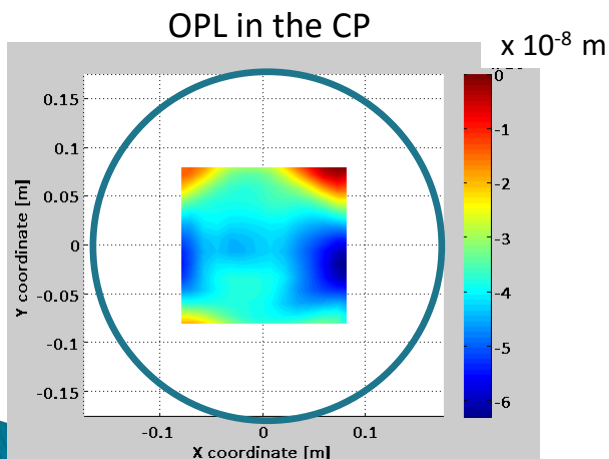
Apply to the map of defects the same procedure developed to extract the optimized heating pattern for thermal effects, extended to the 3D case (computationally very expensive).



P-V about 60 nm
RMS \sim 3 nm!



Total power: 2 W

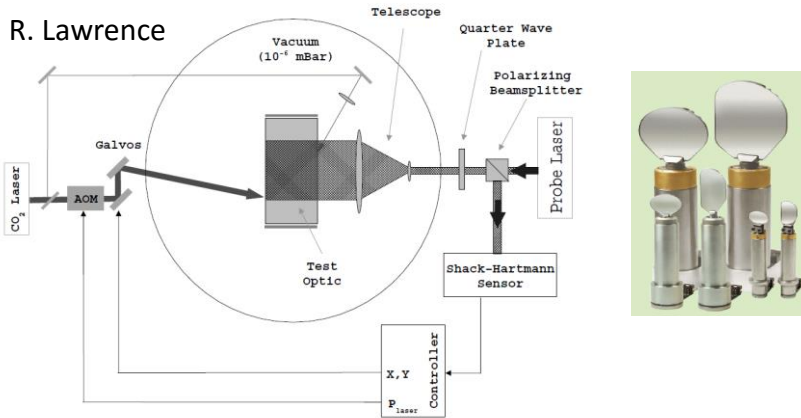


Leftover peak-to-valley is 3.5 nm and RMS is about 0.3 nm (to be compared to the 2 nm requirement)

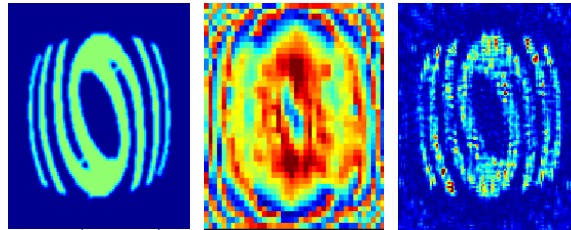
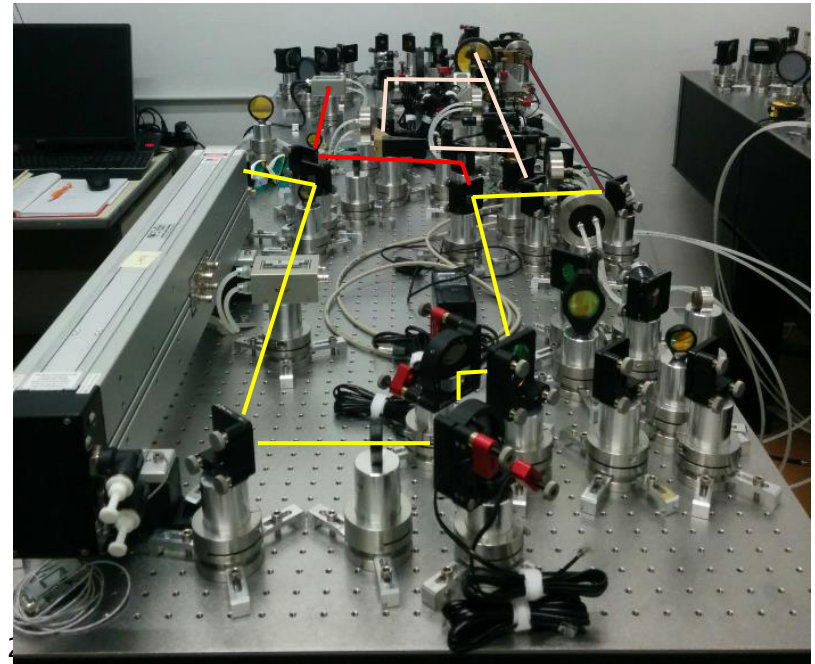
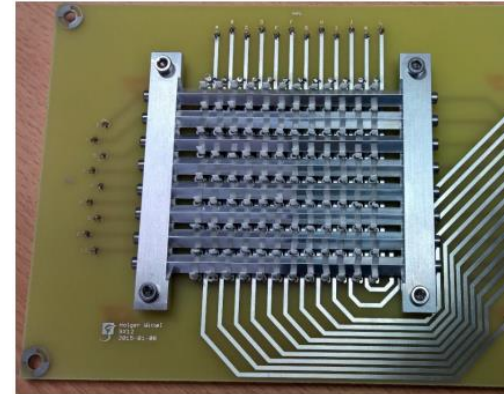
Heating pattern generation techniques

- ▶ CO₂ laser based techniques:
 - Scanning system – under construction;
 - MEMS deformable mirrors.
- ▶ Heater arrays

R. Lawrence



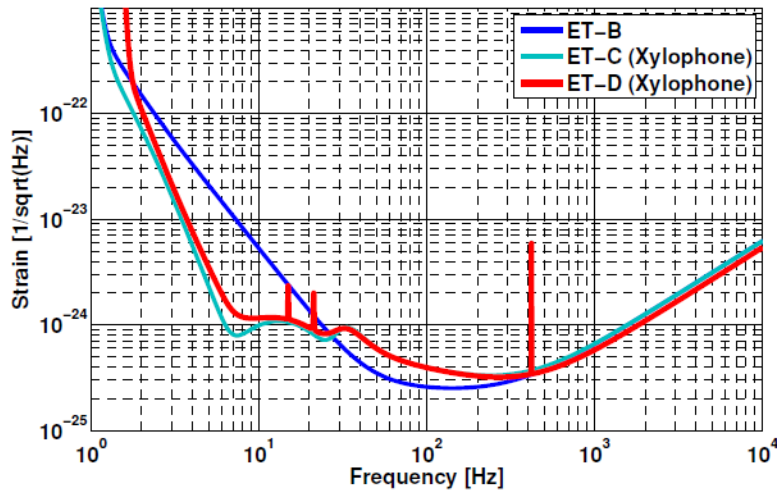
GEO heater array (LIGO-G1500461)



The simulation is obtained for flat incident intensity on an array of 40x40 micromirrors with 1 mm side

What about 3rd generation detectors?

- ▶ ET conceived as a 2-tone configuration (CQG 28, 094013, 2011).
 - High frequency detector:
 - High optical power
 - Room temperature
 - LG₃₃ beam
 - Low frequency detector:
 - Low optical power
 - Cryogenic
 - Silicon (?) test masses
 - TEM₀₀ beam

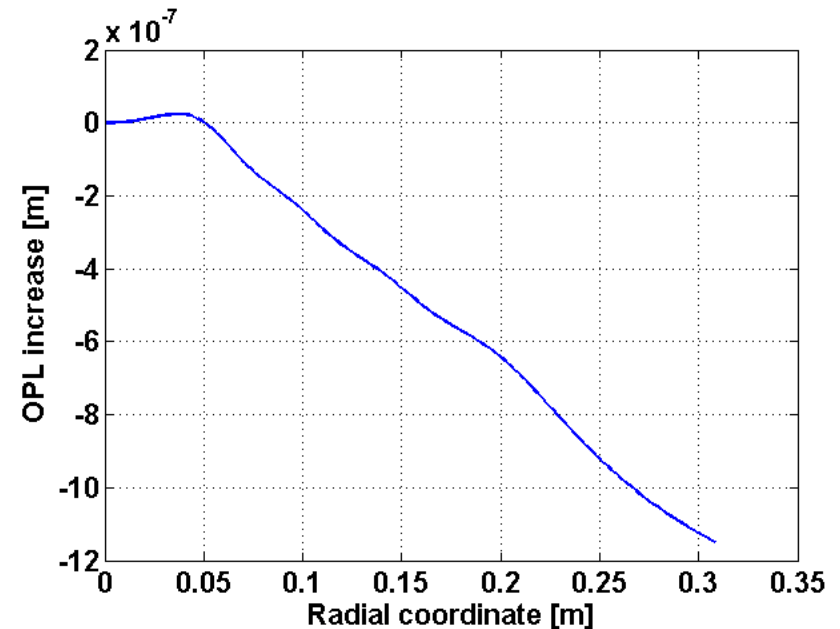
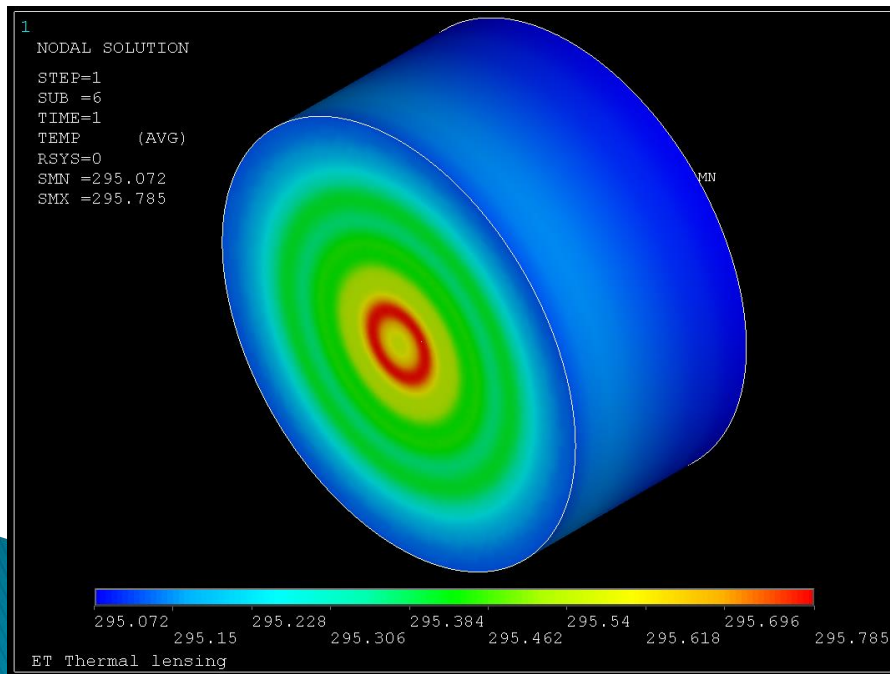
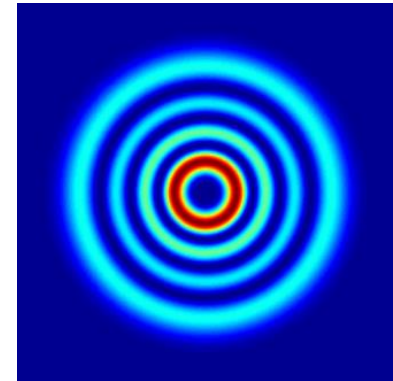


Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused silica	Silicon
Mirror diameter/thickness	62 cm/30 cm	min 45 cm/TBD
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10%	20%
Quantum-noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1 × 10 km	2 × 10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG ₃₃	TEM ₀₀
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Partial pressure for H ₂ O, H ₂ , N ₂	10 ⁻⁸ , 5 × 10 ⁻⁸ , 10 ⁻⁹ Pa	10 ⁻⁸ , 5 × 10 ⁻⁸ , 10 ⁻⁹ Pa
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for f > 1 Hz)	5 × 10 ⁻¹⁰ m/f ²	5 × 10 ⁻¹⁰ m/f ²
Gravity-gradient subtraction	none	none

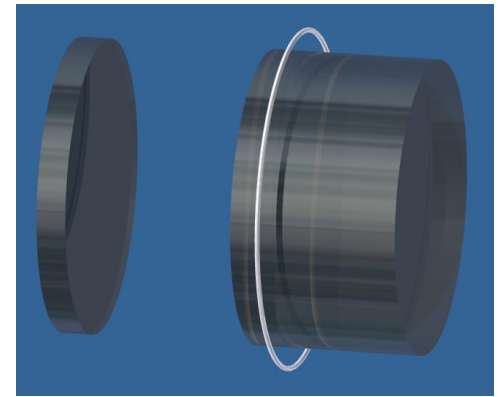
Thermal effects in ET-HF

▶ ET-HF uses

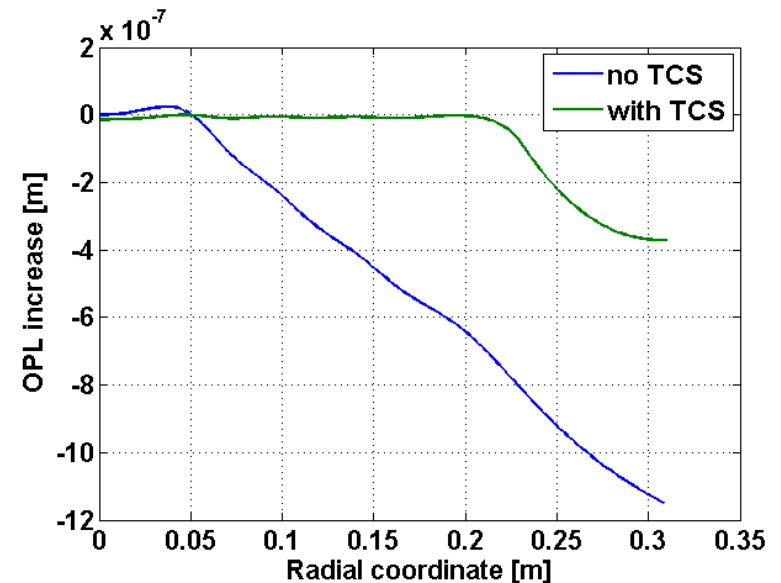
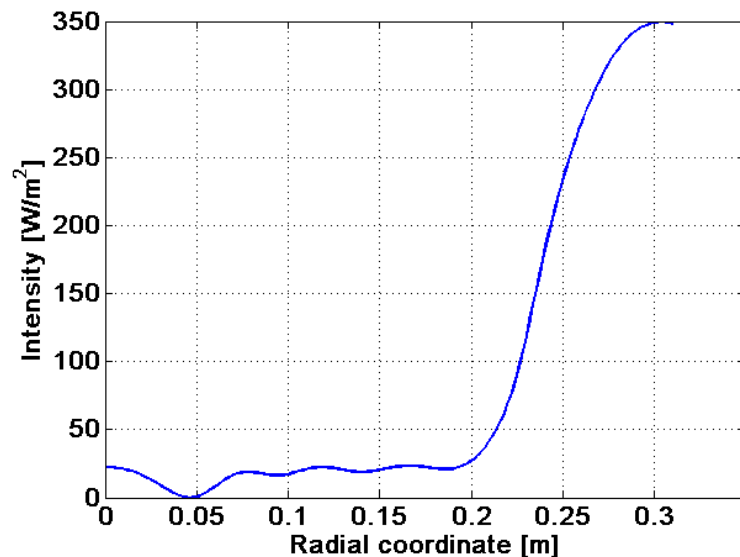
- Helical LG_{33} modes
- Fused silica test masses
- Considering 3MW in the FP cavity and coating absorptions of 0.5ppm, absorbed power is 1.5W (3 times higher than in AdVirgo)



AdVirgo-like TCS



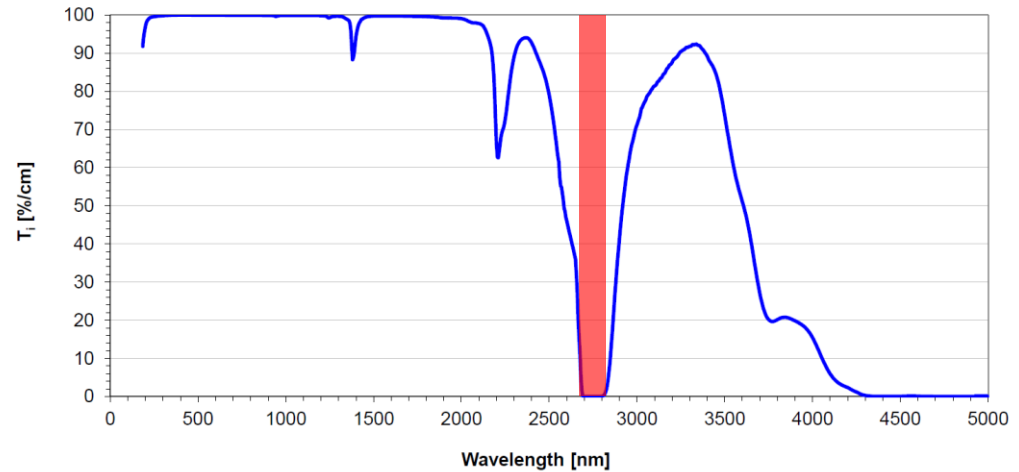
- ▶ Compensation plates properly heated



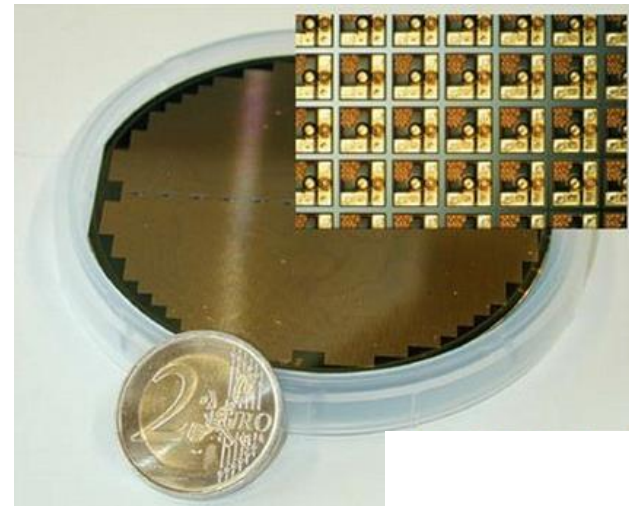
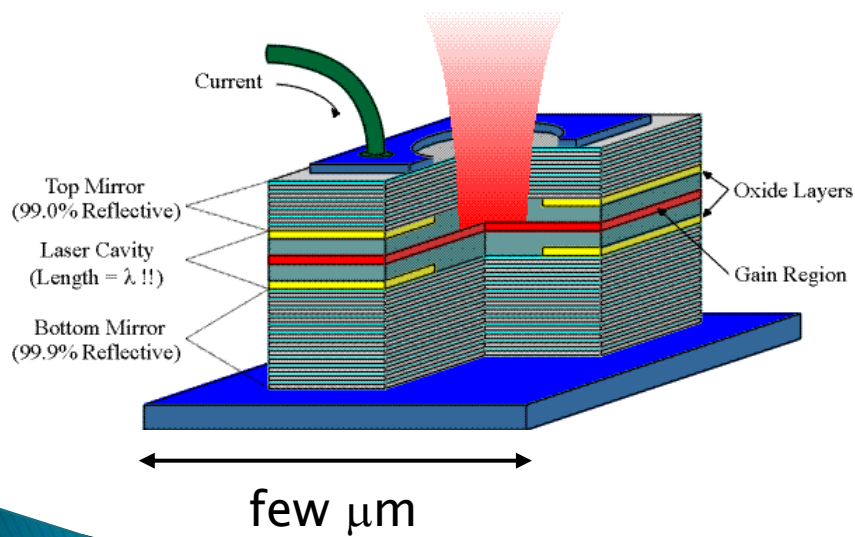
- ▶ Ring heaters to correct mirrors' radii of curvature
- ▶ Moreover, LG₃₃ modes inside FP cavity extremely sensitive to low-order optical aberrations:
 - Current polishing techniques are not enough to guarantee the required cavity mode quality (PRD 87, 082003, 2013);
 - Need for an additional actuator to correct these defects.

Next generation actuators

- ▶ New possibilities
 - Abandon FIR sources
 - Exploit absorption band around $2.7\ \mu\text{m}$
 - VCSELs arrays



Vertical-cavity surface-emitting laser



VCSELs are also built in arrays with up to thousands of elements on a single chip

Summary

- ▶ Wave-front aberrations are an unavoidable annoying presence in our interferometric GW detectors;
 - Limit both the controllability and the sensitivity of the instruments.
- ▶ They can be compensated for using thermal actuators (FIR lasers, ring heaters):
 - Optimized heating patterns can be found by means of finite element modeling;
 - Nearly optimized heating patterns can be generated using “standard” refractive optical systems;
 - necessity to generate also non-symmetric heating patterns (laser scanning system, MEMS, heater arrays).
- ▶ In third generation ITFs, use of LG_{33} modes to reduce thermal noise will pose more stringent requirements on adaptive optical systems.
- ▶ New technologies (VCSELs arrays) can represent promising solutions.

The End

Contact information:

Alessio Rocchi - INFN Roma Tor Vergata

Tel: +39 06 94038149

E-mail: alessio.rocchi@roma2.infn.it