Thermal Corrective Devices for Advanced Gravitational Wave Interferometers

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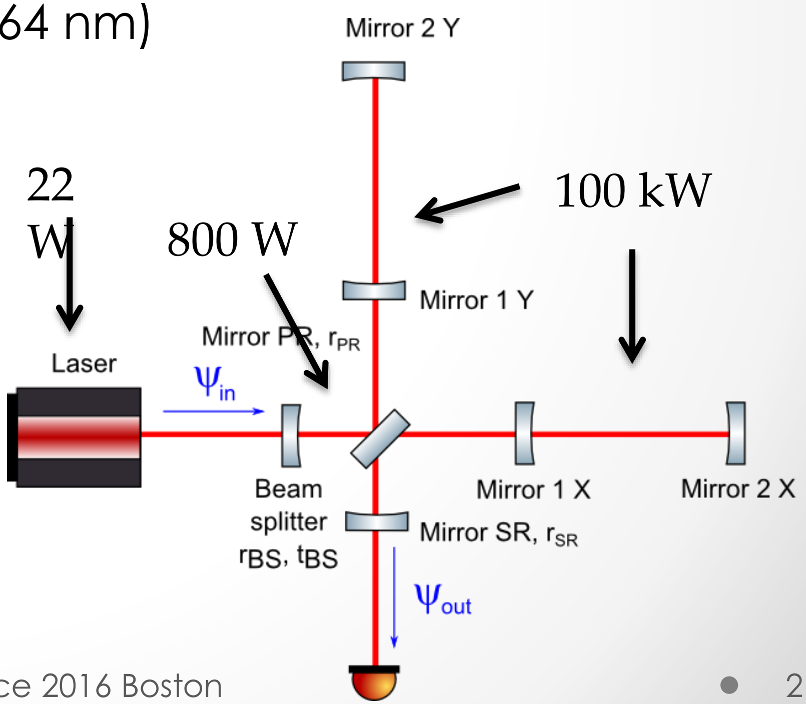
6th October 2016

COMSOL Conference 2016 Boston

1. Advanced Gravitational Wave Detectors

- Based on resonant optical cavities with suspended optics under vacuum: **dual recycling Michelson interferometer**
- On the way to the 2nd Observing run:
  2 **LIGO** detectors in operation, **Virgo** detector will join in 2017
- First observations started recently at LIGO: **GW150914**, **GW151226**
- Facilities use **high power laser** (CW 1064 nm)

LIGO Livingston (LA)



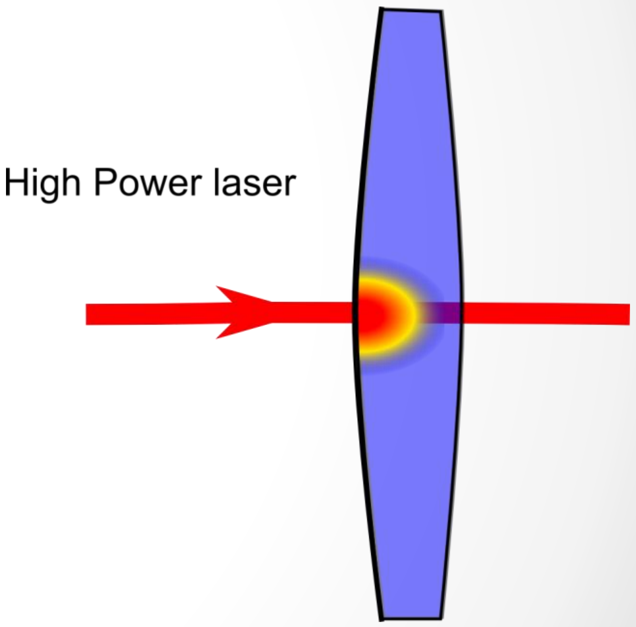
1. Advanced Gravitational Wave Detectors

High laser power brings thermal effects:

- Thermal load on a Test Mass: **Heating of the substrate**
  - Coating and substrate absorb the beam power
  - Index of refraction of the mirror changes
    - produces a **thermal lens**
    - and potentially **high order modes**
  - Thermal expansion
    - changes the **curvature** of the mirror

- In the main cavities, thermal lensing ~ 0.8 μm (focal length 5 km)

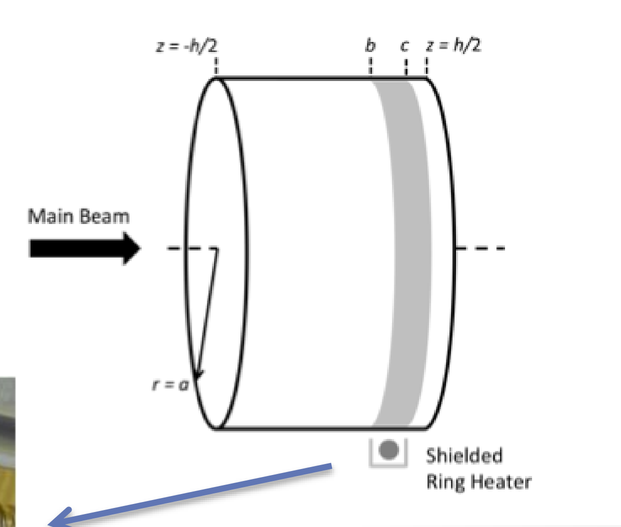
- Thermal load changes over time

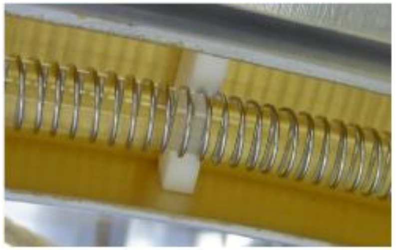


→ **We need adaptive optics devices to correct for in-situ aberrations and input mode matching**

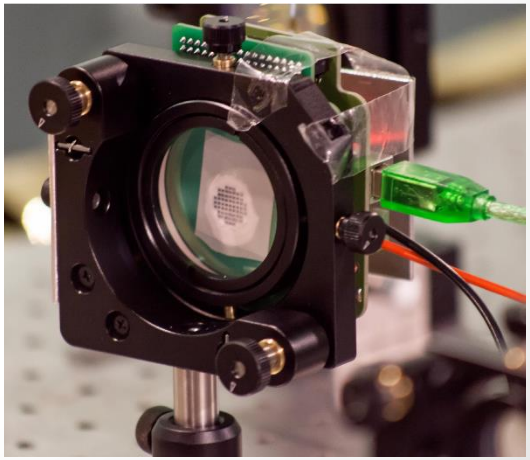
2. Thermal devices for aberration mitigation

- **Ring heater**: *installed*
  - Around the main mirrors of the cavities
  - Target: correction of the Radius of Curvature
  - Two semispherical heating segments





- **Thermally deformable mirror:** *prototype*
  - Outside the cavity
  - Target: correction of higher mode aberrations for mode matching
  - Set of 61 resistors in the back of a 2" Ø mirror

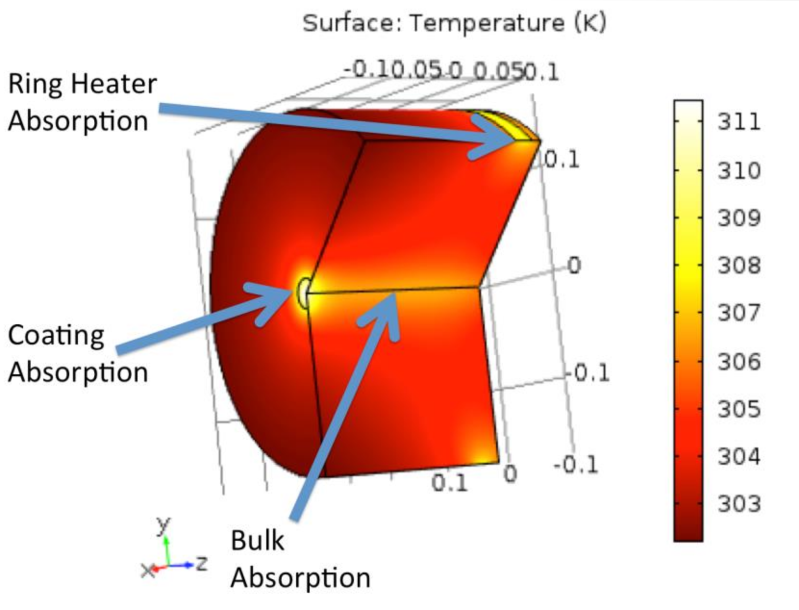


3. Ring Heater

- **Simple analytical model:** $$\rho C \frac{\partial T}{\partial t} - K \nabla^2 T = 0$$
  - From the heat equation
  - Both in steady state and time dependent model
  - One circular segment

  → Useful to predict the general behavior of the system

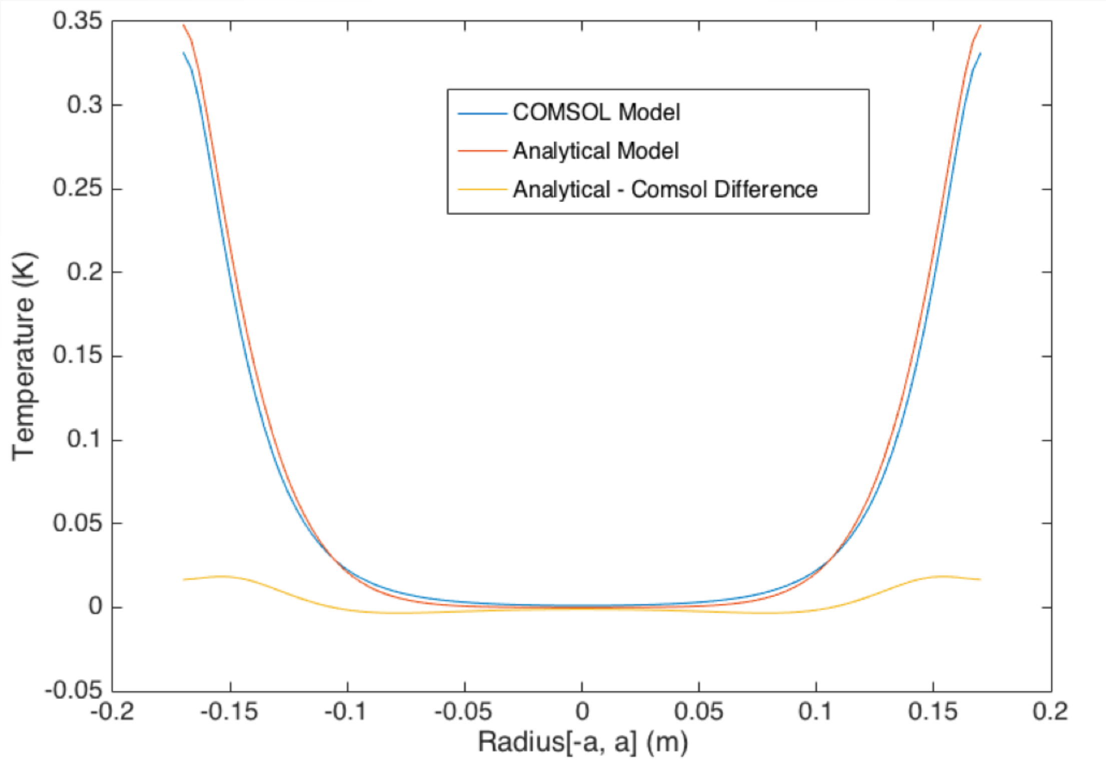
  - Limitations:
    - Design very limited
    - Axis-symmetry



- **COMSOL® Model**

Double purpose of
validate our analytical model and
lay the foundations for a more complex model

3. Ring Heater



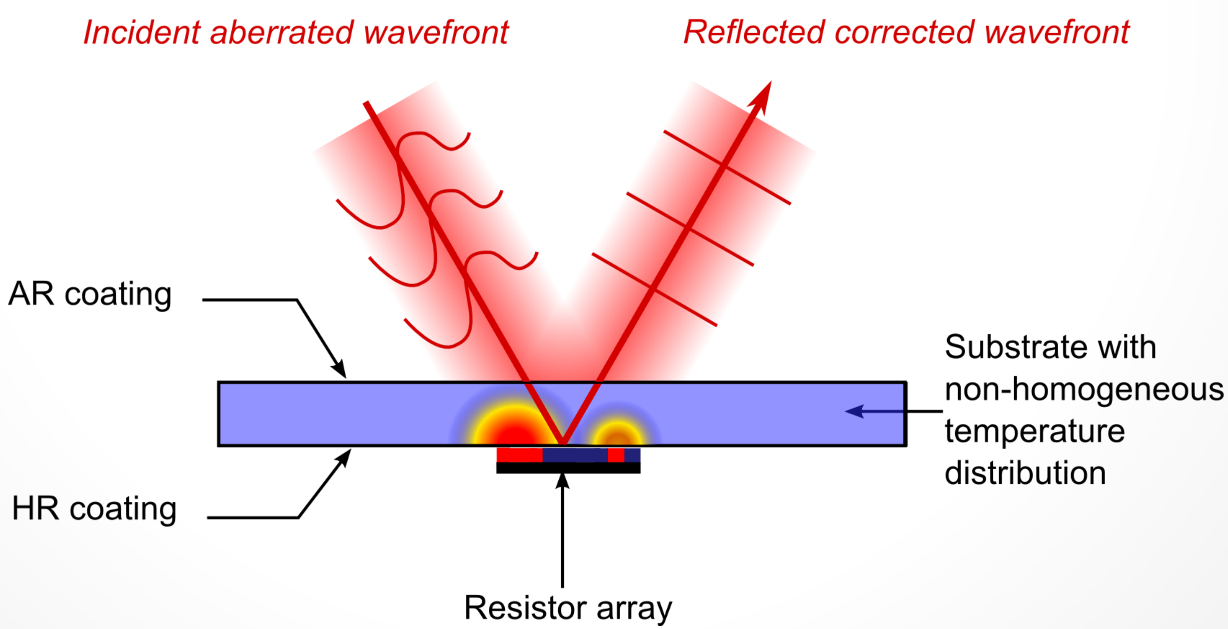
- **Main time constant:**
  - 27 hours to reach steady state
- **Very good agreement between our analytical model and COMSOL**
  - at t = 1000 s , relative difference below 5 %
  - At t = 100000 s, relative difference below 1 %

4. Thermally Deformable Mirror

- Actuation:
  Control of the **optical path length** via the **substrate temperature**

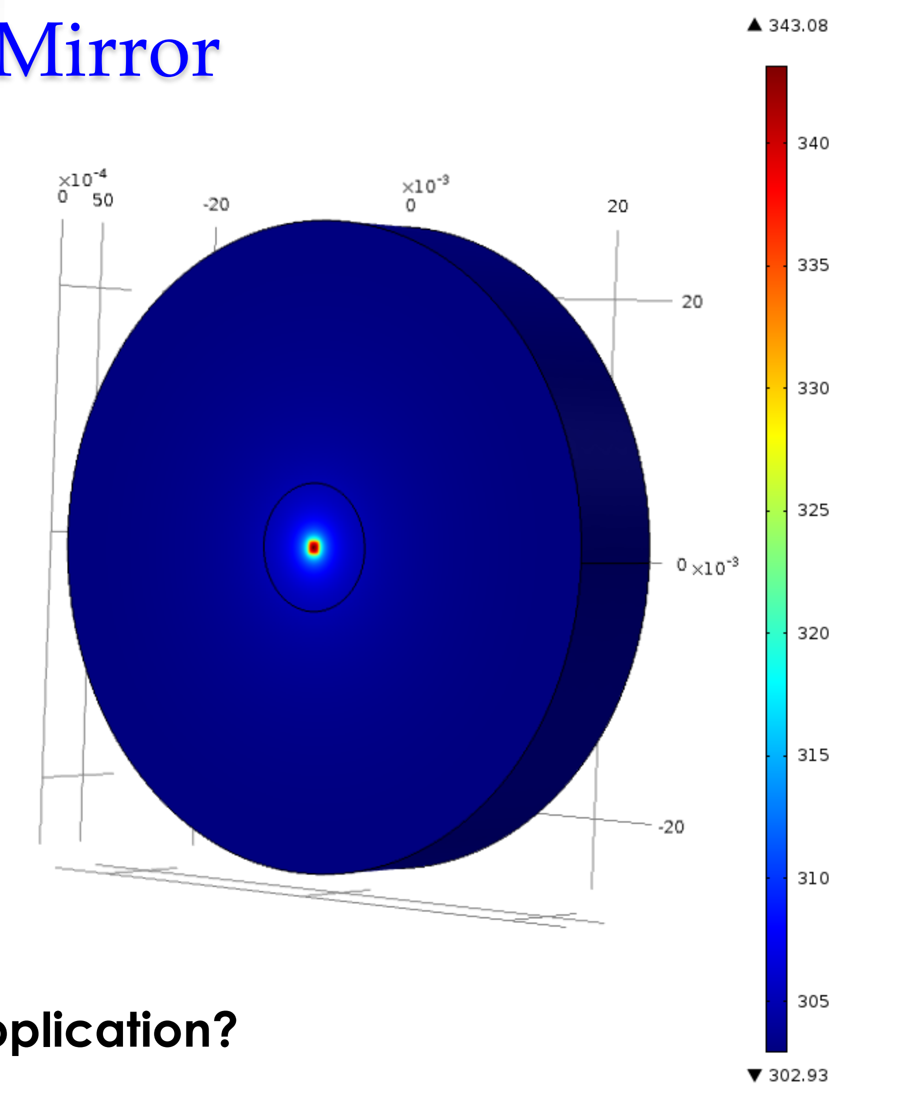
$$\text{OPD} = \left[\frac{\partial n}{\partial T} + a(1+u)(n-1)\right] \cdot \int_{z=0}^{d} \mathrm{D}T(x,y,z)\,\mathrm{d}z$$

Opto-mechanical parameters   Temperature field



4. Thermally Deformable Mirror

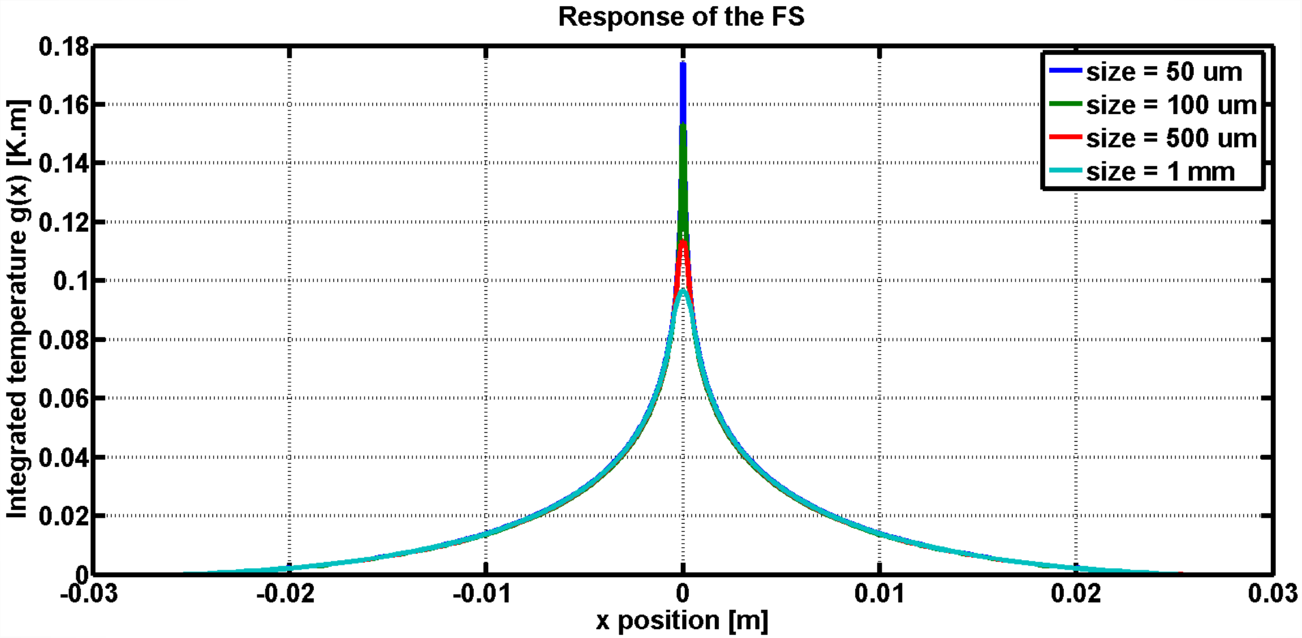
- **COMSOL® Model**
  - Finite dimensions
    - 24.5 mm radius
    - 10 mm thick
  - No axis-symmetric assumption
  - Square actuator
  - 100 mW coupled



- **Effect of the actuator size?**
- **What is the best substrate for our application?**
  - Moderate temperature increase
  - Large amplitude of the optical response

4. Thermally Deformable Mirror

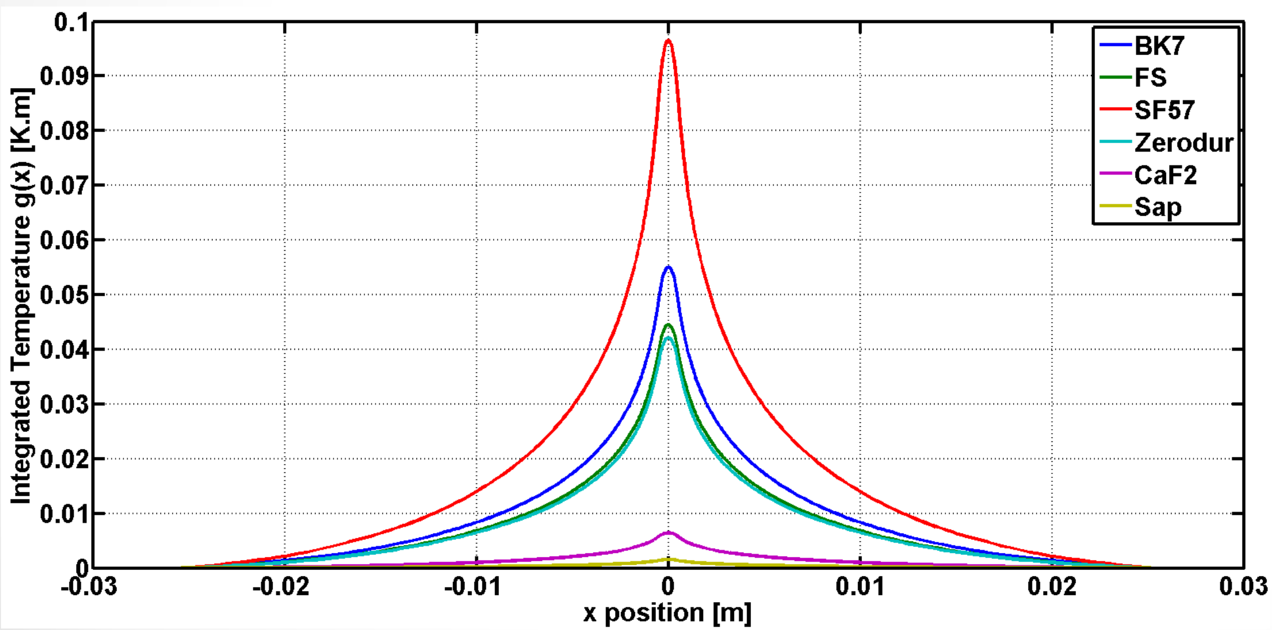
- Global shape of temperature integral dominated by the **heat radiation**



- Shape characterized by:
  - The width at half maximum (HWHM)
    - depends on actuator size
    - mostly independent from the thermal properties of the substrate
    - independent from the thickness
  - the amplitude

4. Thermally Deformable Mirror

- Amplitude of actuation :
  - Thermal conductivity K is the most important parameter
  - Material study:
    - Choice of the substrate with the lowest thermal conductivity



Substrate	K [$W.m^{-1}.K^{-1}$]
BK7	1.11
FS	1.38
SF57	0.62
Zerodur	1.46
CaF_2	9.71
Sapphire	40

4. Thermally Deformable Mirror

- Figure of merit: trade-off between
  the **amplitude response** and the **temperature of the substrate**

Material	ΔT (K)	OPD Amplitude (nm)	OPD HWHM (mm)
BK7	52.5	368	2.39
FS	43.1	400	2.41
SF57	91.2	1543	2.32
Zerodur	40.9	603	2.41
CaF_2	9.0	130	2.48
Sapphire	4.6	31	2.49

- Best solutions: Zerodur,
  Fused Silica
  BK7

→ Current prototype: **Fused silica with 61 actuators of 1 mm^2**

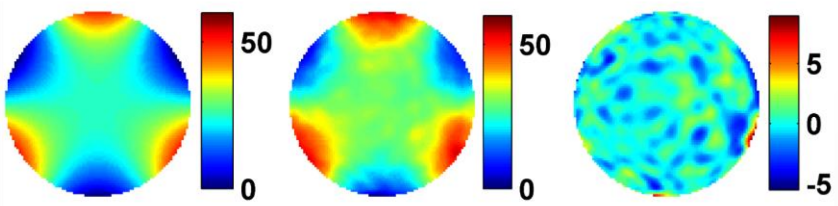
5. Conclusion

Ring heater

- Geometric improvement of the model (shape, fibers, …)
- High order mode estimation
- Kalman filter implementation for the live prediction of aberrations

Thermally Deformable Mirror:

- Choice of material
- Design study from influence functions
- Tests and validations of proof of principle
- Still under development



Zernike mode target   Zernike mode mirror   Residual shape

6. References

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- Performance of a thermally deformable mirror for correction of low-order aberrations in laser beams,

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- Thermally Deformable Mirrors: a new Adaptive Optics scheme for Advanced Gravitational Wave Interferometers

  M Kasprzack