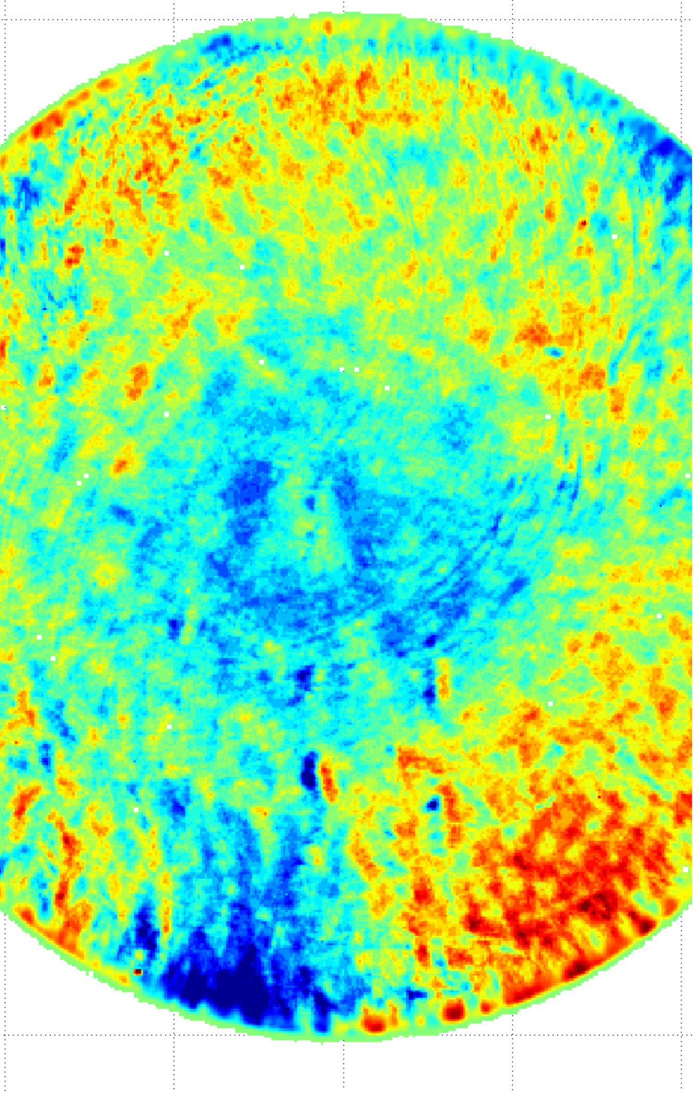
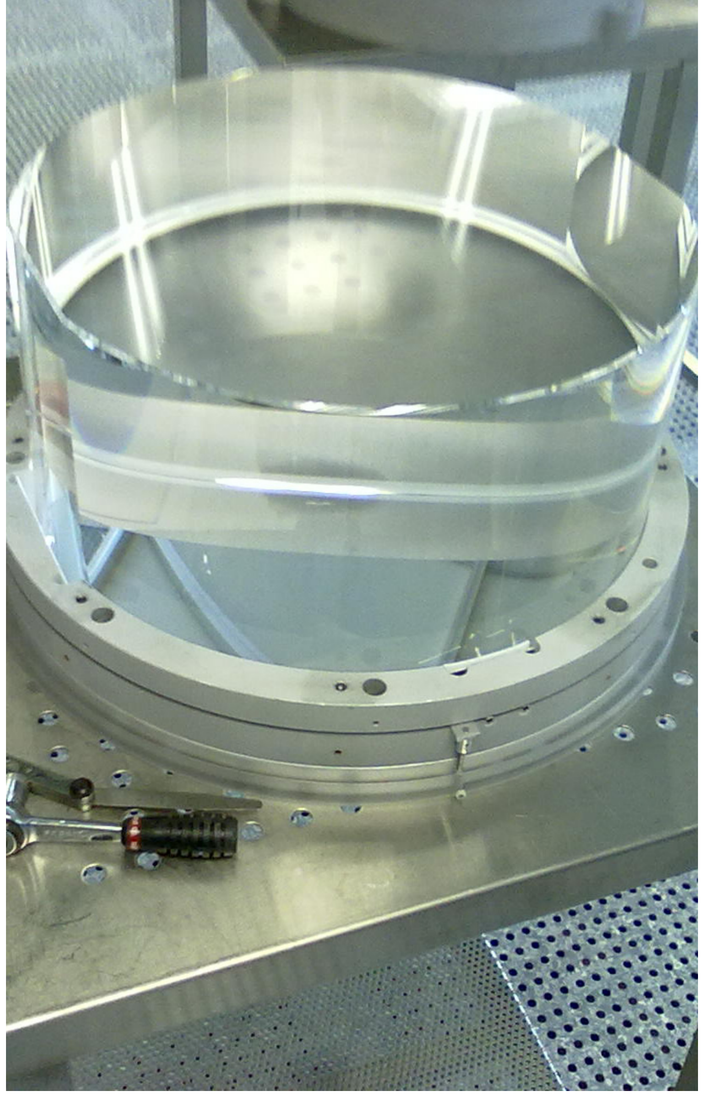
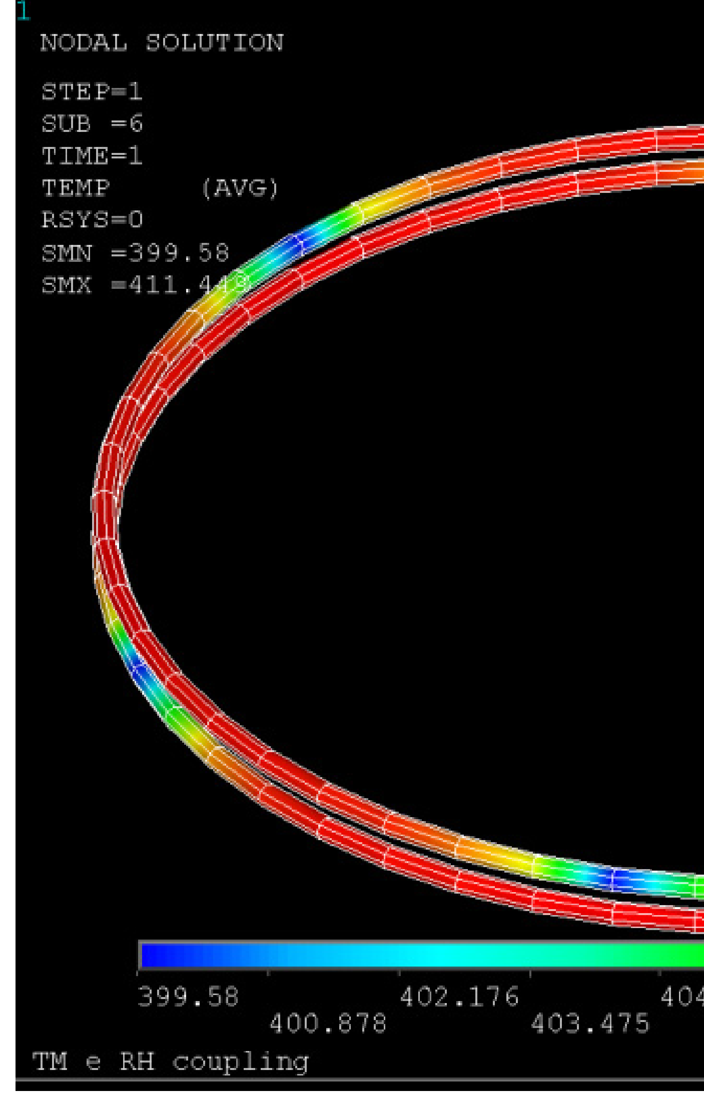




Living with aberrations

A collection of personal thoughts - Jerome Degallaix
with materials from LIGO/Virgo/Kagra

GWADW 2013

During the following 25 minutes…

The source and handling of aberrations in 3 generations of GW interferometers.

Special focus on the design and expectation for the Advanced detectors.

Only a few words about the consequences on the interferometer operation (next slide)

Multiples consequences

Aberrations are due to any deviations from perfect optics (radius of curvature errors, surface errors,...)

- Distorted the shape of the laser beam
  - decrease the mode matching (less light available)
  - decrease the recycling gain (SB in MSRC)
  - lower the contrast (with excess light at the dark port)
  - decrease the common Michelson mode rejection
- Diffused light
  - increase the optical loss
  - more details in the previous talk

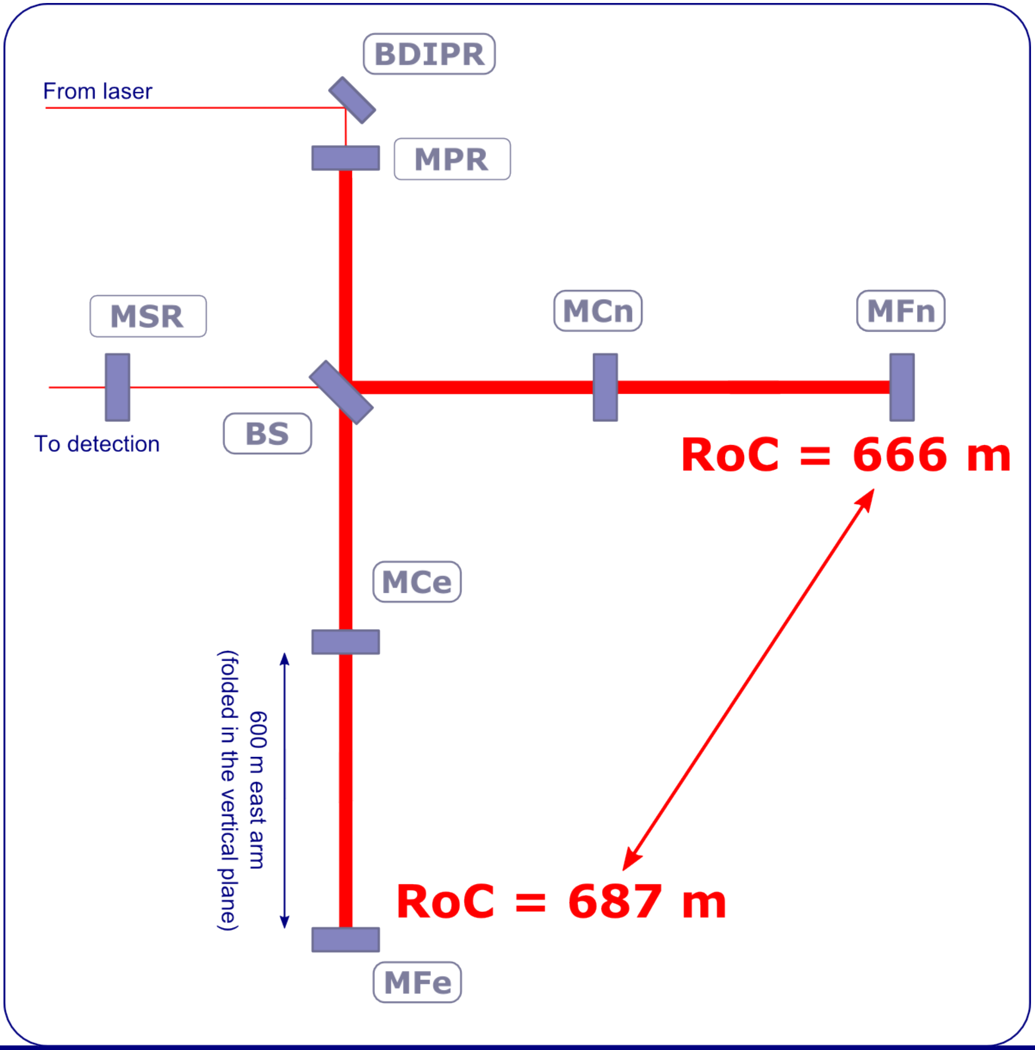
I

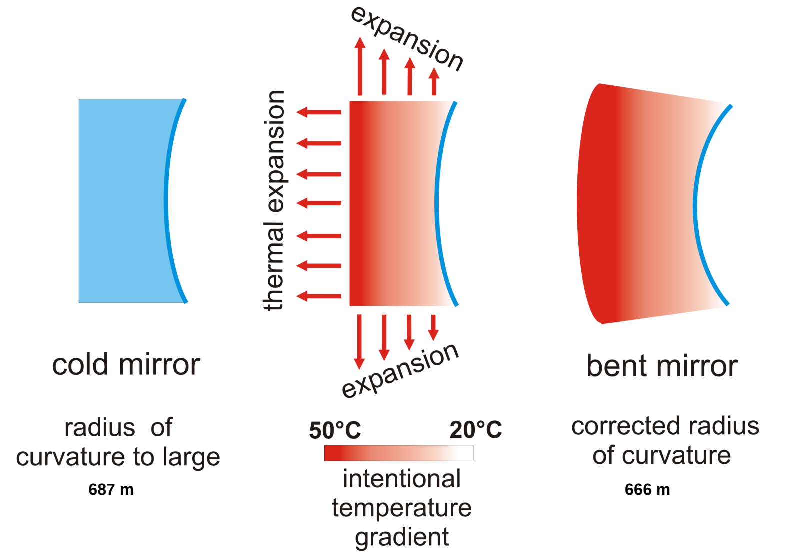
What we learned and achieved with the first generation of detectors (aberration wise)

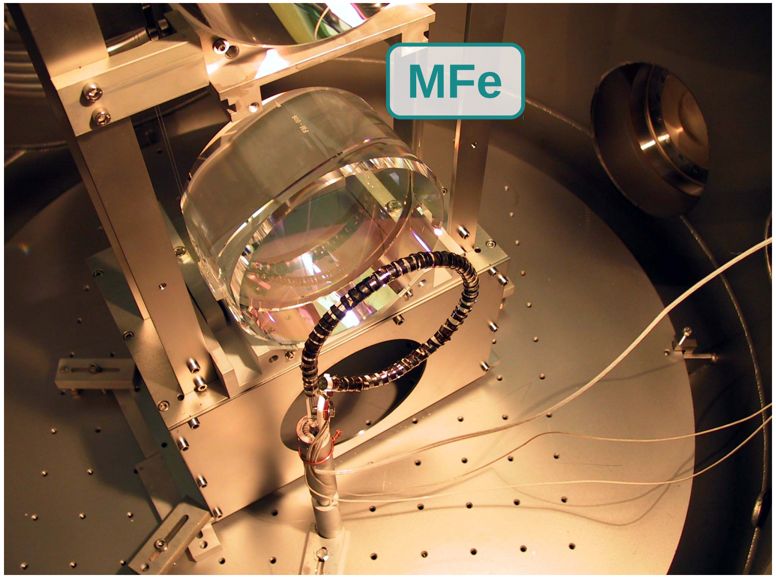
Let's blame the polisher!

Bad surprise: differential RoC in the 2 arms...

The GEO600 case





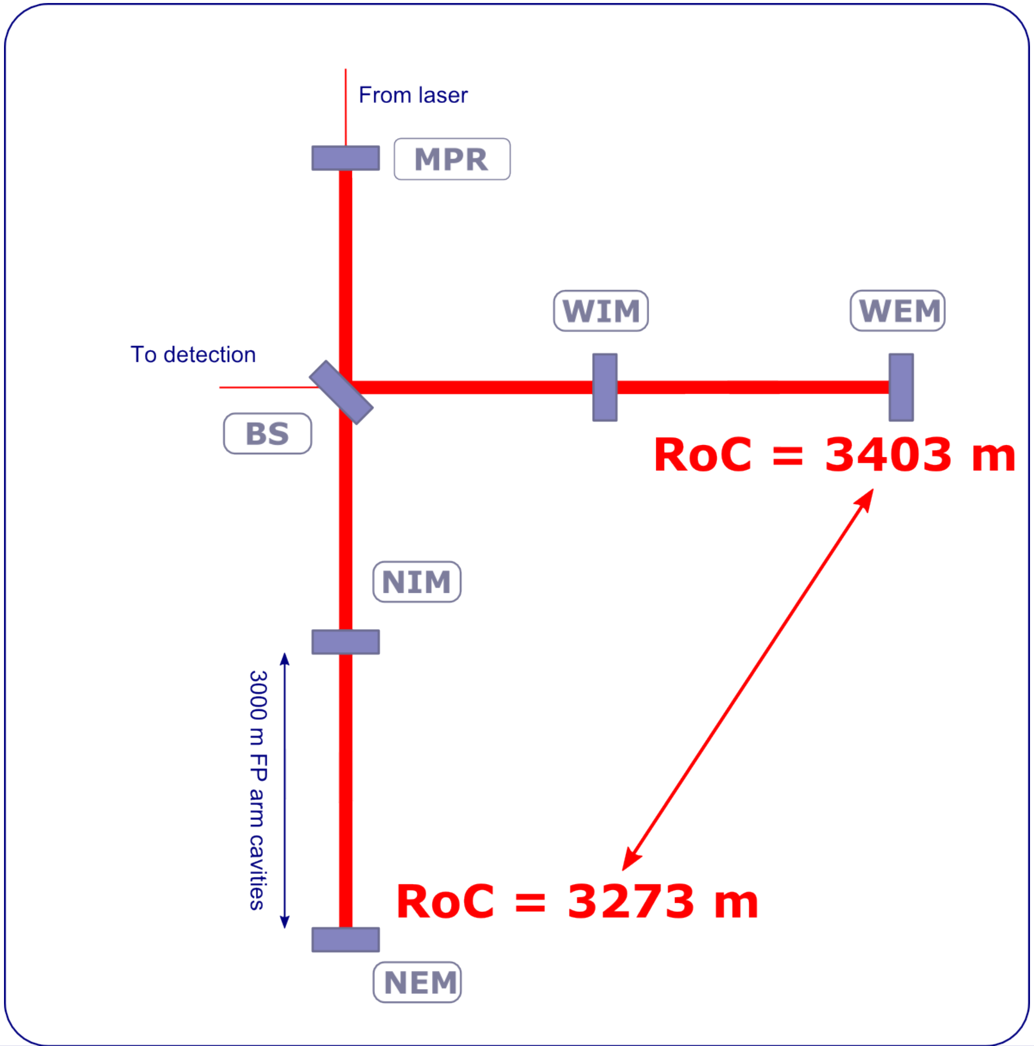


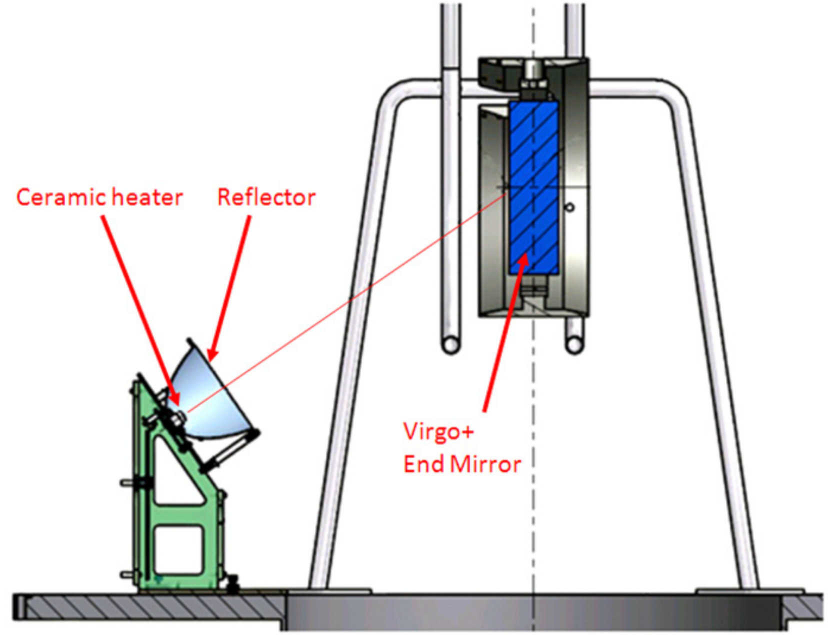
Thermal correction of the radii of curvature of mirrors for GEO 600, http://stacks.iop.org/0264-9381/21/i=5/a=090

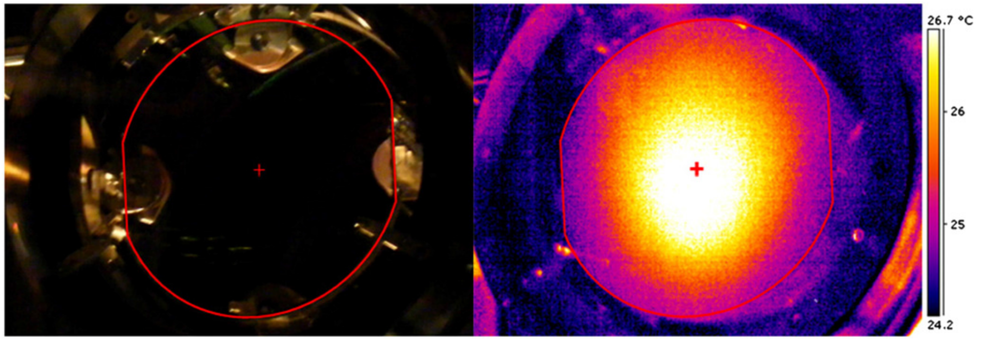
Let's blame the polisher!

Same story but with different mirror names

The Virgo+ case







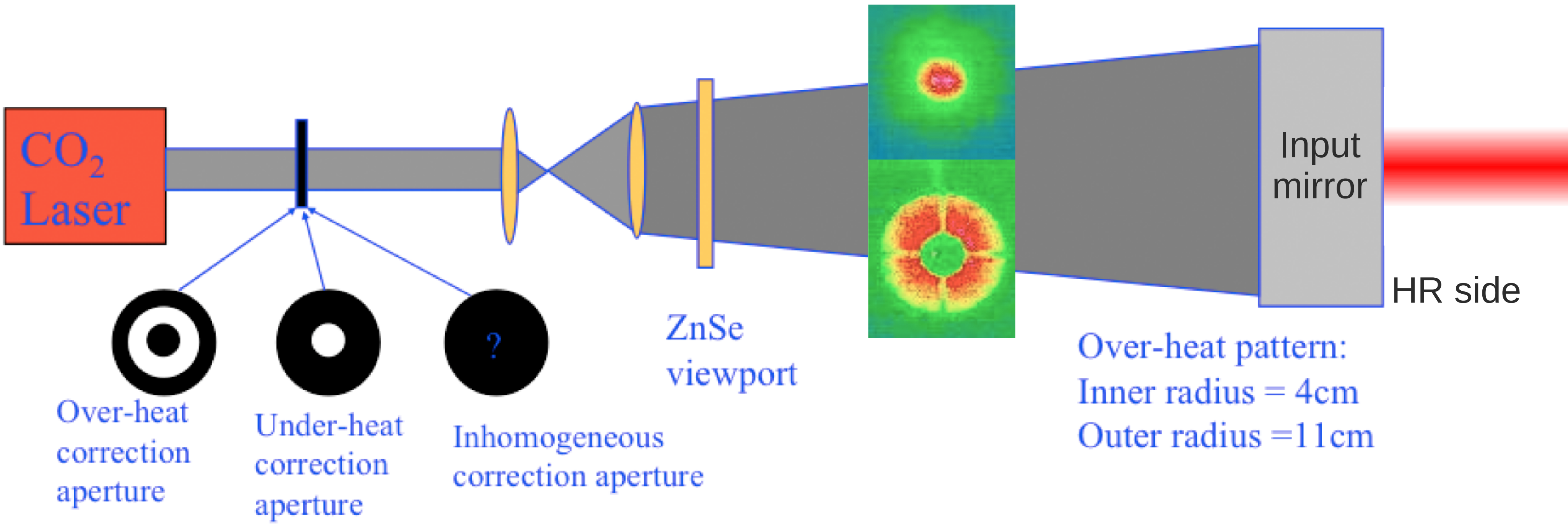
Temperature distribution

Power up!

Aberrations induced by the optical absorption:

- change of RoC
- wavefront distortions induced by the IM

The initial Thermal Compensation System (TCS):

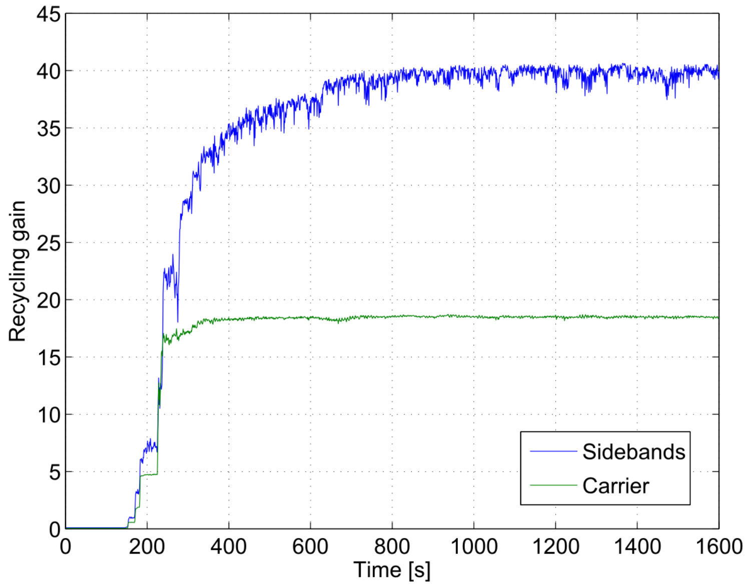


Same principle for (E)LIGO and Virgo(+)

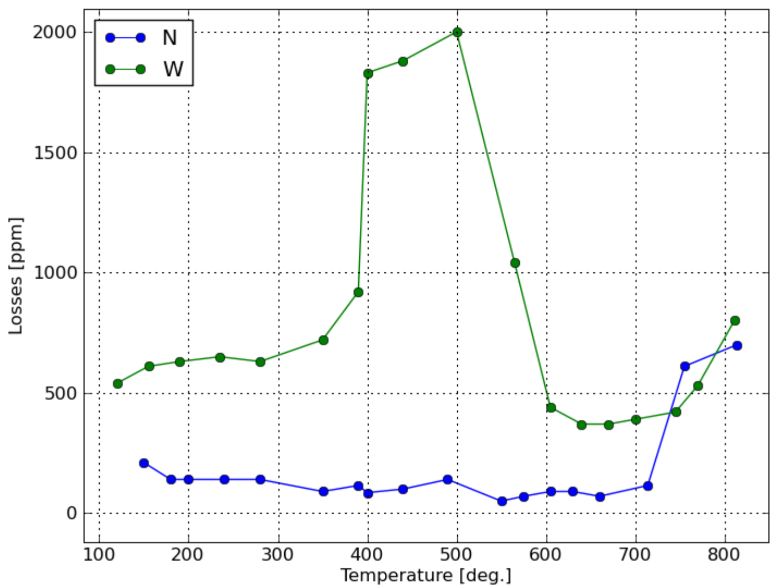
The lesson of the initial interferometers

Tight up the RoC specifications!

TCS works:



Possibility to tune
in situ the mirrors RoC
(and the losses):

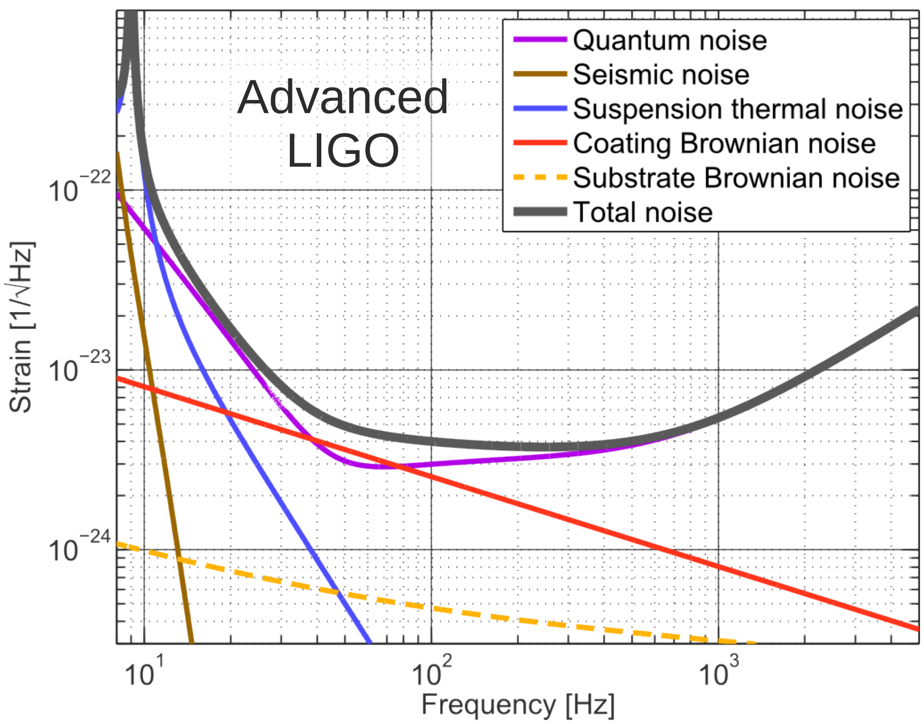


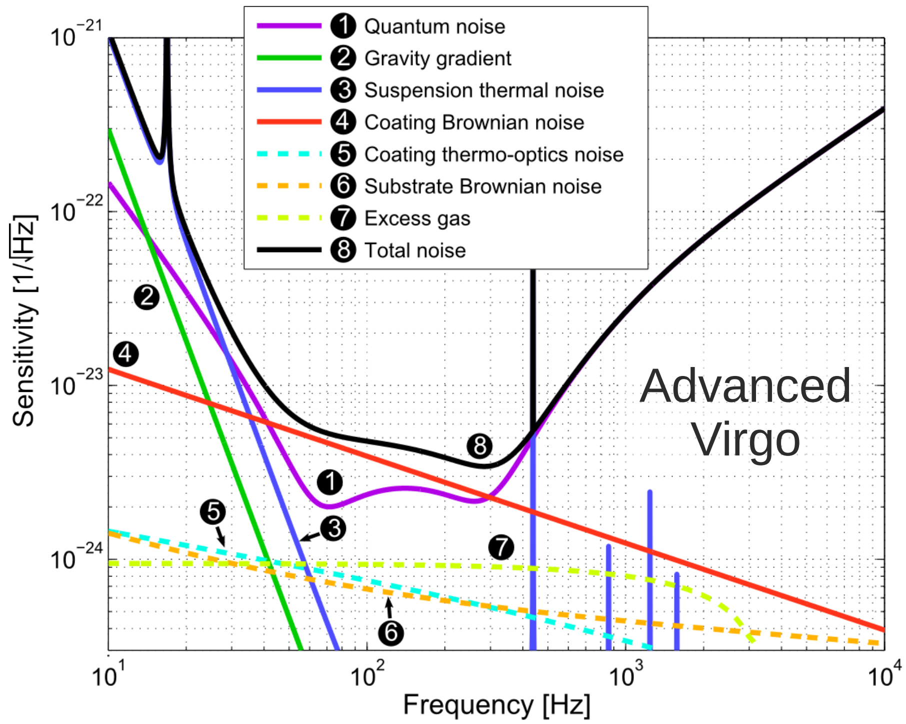
II

How we designed and achieved the second generation

Getting the right level of aberrations

Sensitivity 10 times lower, do we need aberrations 10 times lower as well ?





Level of acceptable aberration not straight forward to derive from the sensitivity!

From global requirement to mirror specifications

To not be limited by the aberrations, get the right specifications the mirrors.

Sensitivity / horizon

↓ *Noise coupling*
Dark port power
Cavity gain …

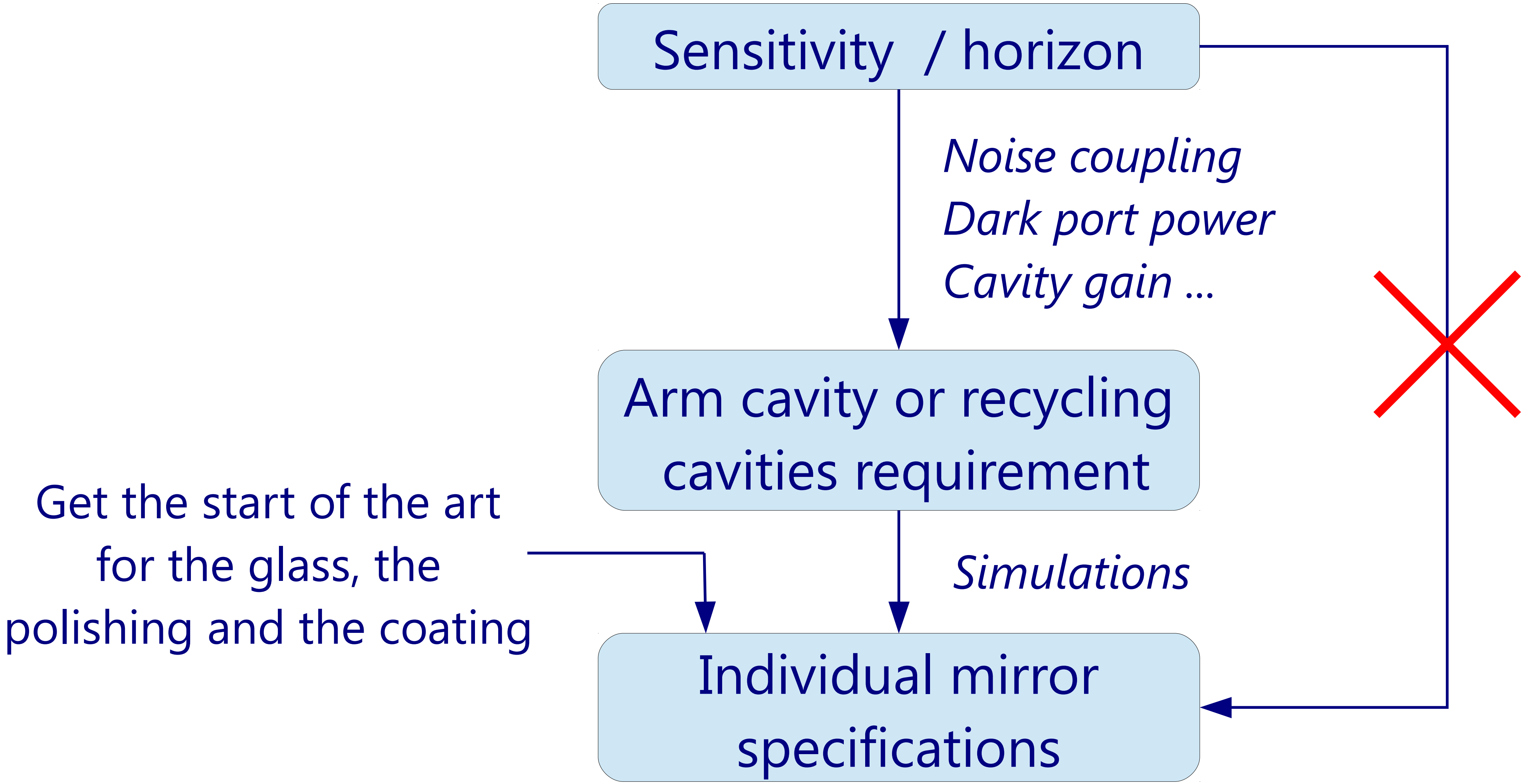
Arm cavity or recycling cavities requirement

↓ *Simulations*

Individual mirror specifications

From global requirement to mirror specifications

To not be limited by the aberrations, get the right specifications the mirrors.



Comparing the mirror specifications

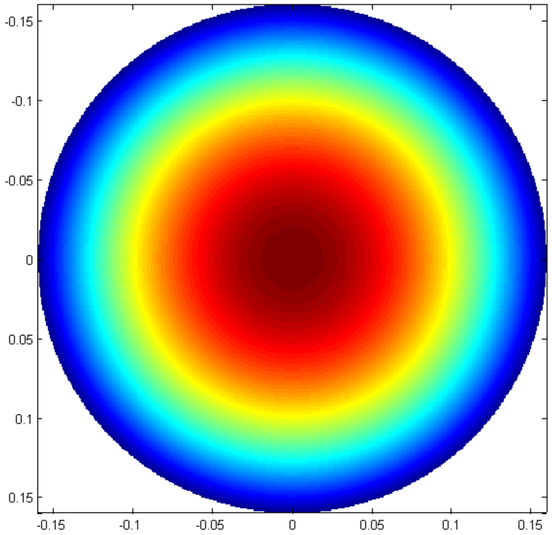
Example of the Virgo / Advanced Virgo end mirror

	Initial Virgo	Advanced Virgo
RoC tolerance	6%	1%
Surface flatness	8 nm RMS	0.5 nm RMS
Absorption HR	< 5 ppm	< 0.5 ppm
All the RoC within	-	0.2%

Effect of aberrations in the arm cavities

Kilometer long Fabry Perot cavity. Different size of the surface errors have different consequences

RoC error

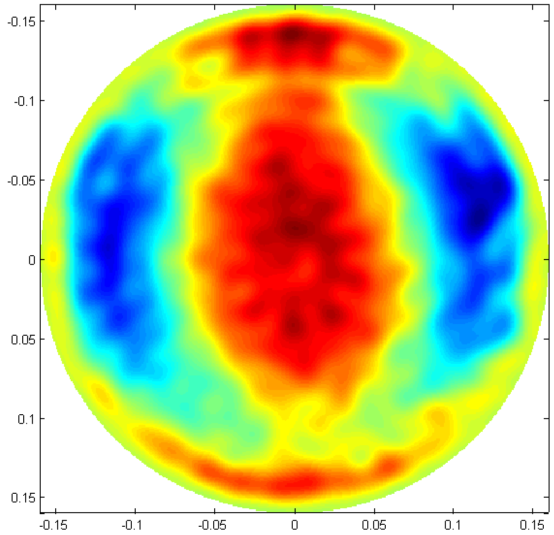


Bad contrast

(can be corrected)

Low frequency error

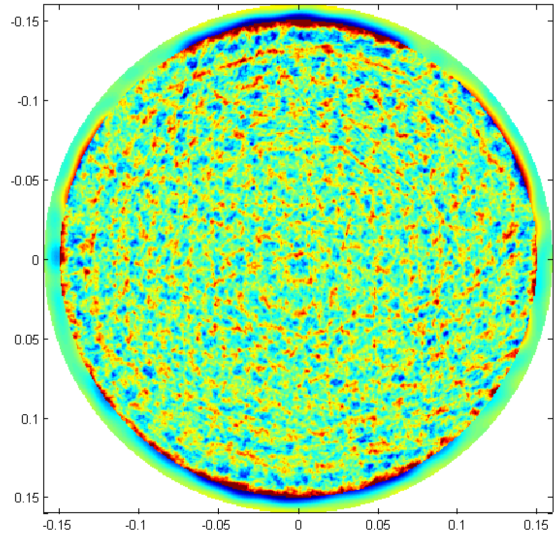
($f < 50\ m^{-1}$)



Bad contrast, distorted reflected beam

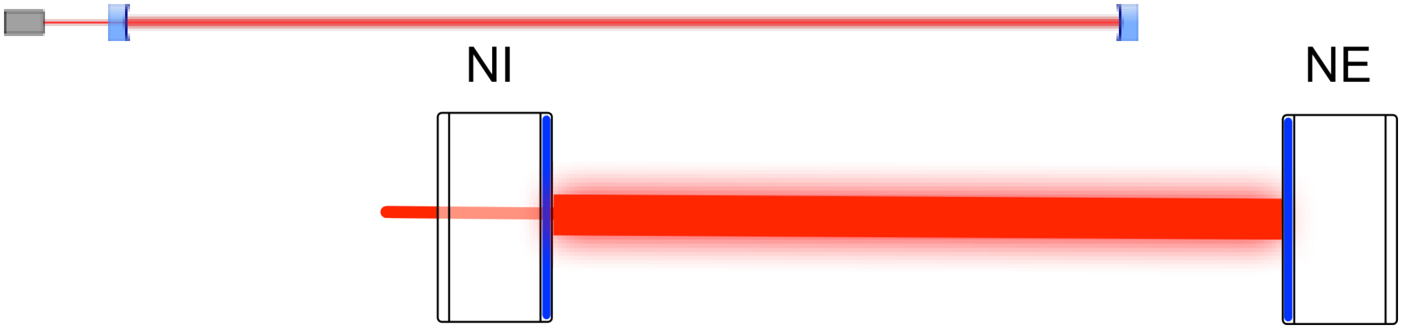
High frequency error

($f > 50\ m^{-1}$)



Light lost

The arm cavities polished substrates



The arm cavity substrates for Advanced interferometer are near perfect after polishing!

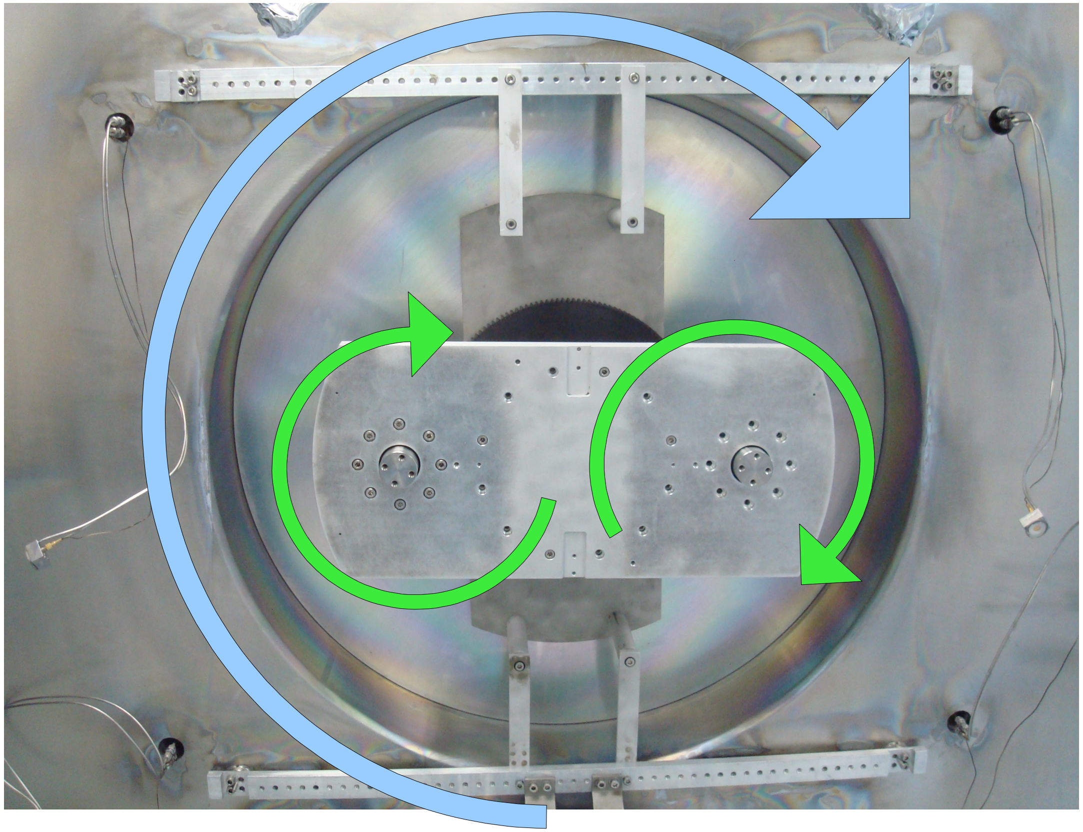
Following the Advanced LIGO experience:

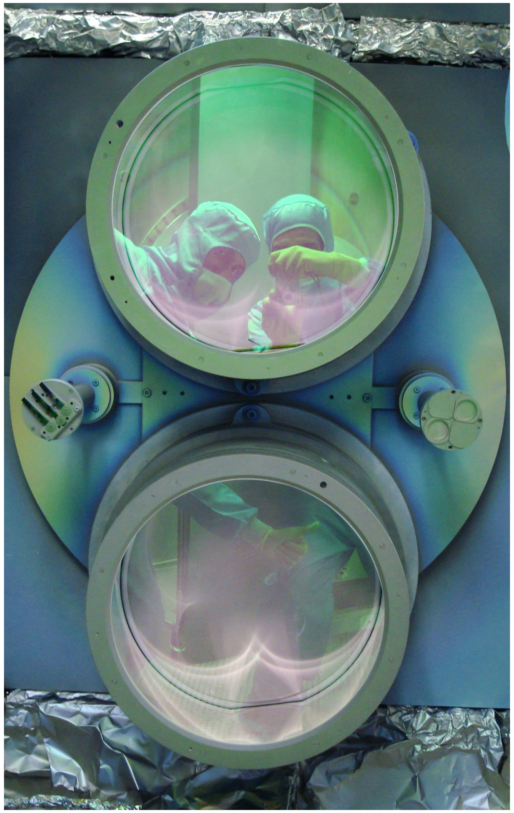
- All the RoC within 0.4 m over 2 km (ITMs)
- Surface RMS < 0.3 nm
- Roughness < 0.1 nm

Very low round trip loss: ~ 5 ppm

Start of the art coating (LMA version)

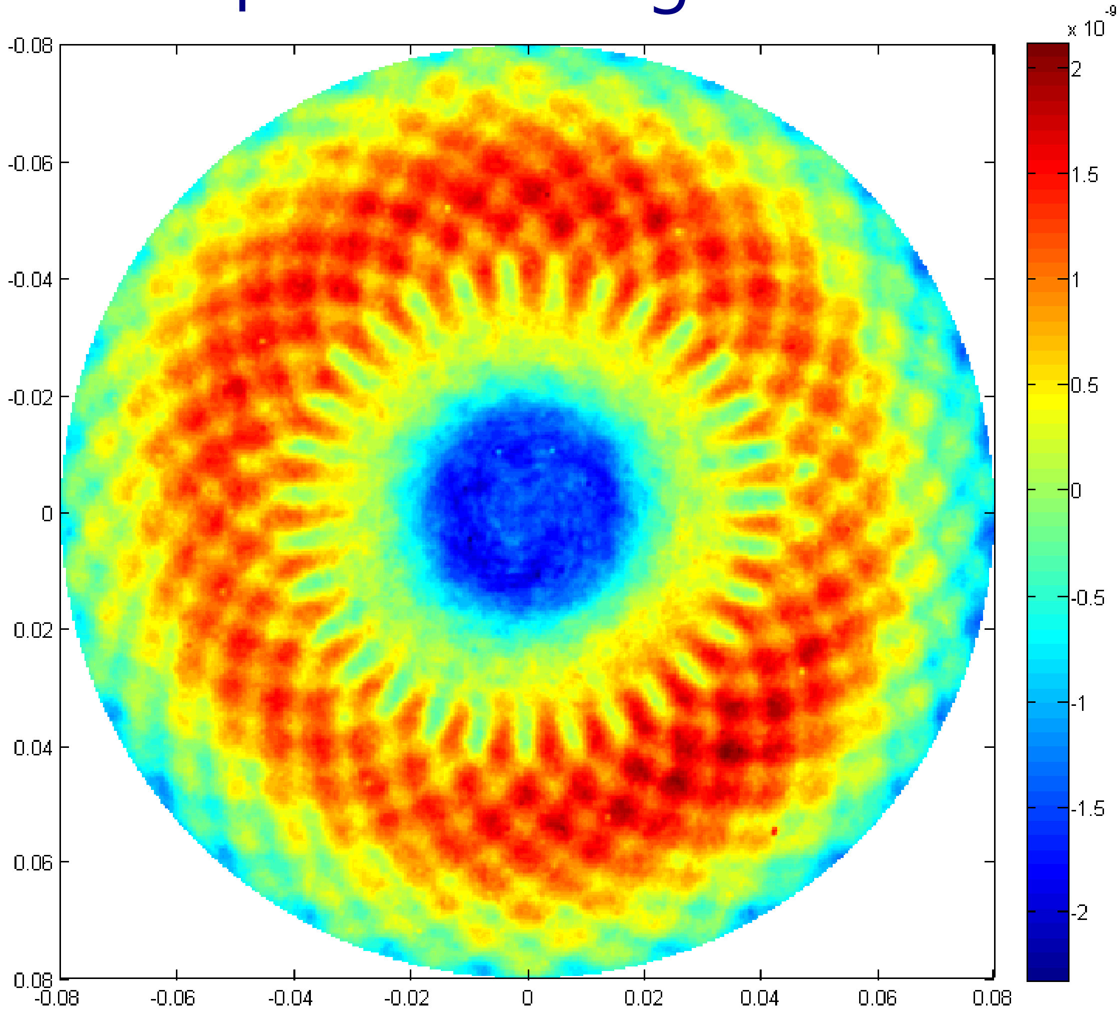
- Two mirrors coated at the same time
- Planetary motion to increase the uniformity
- Example on the most challenging mirror: the End Mirrors





A close look at the coating

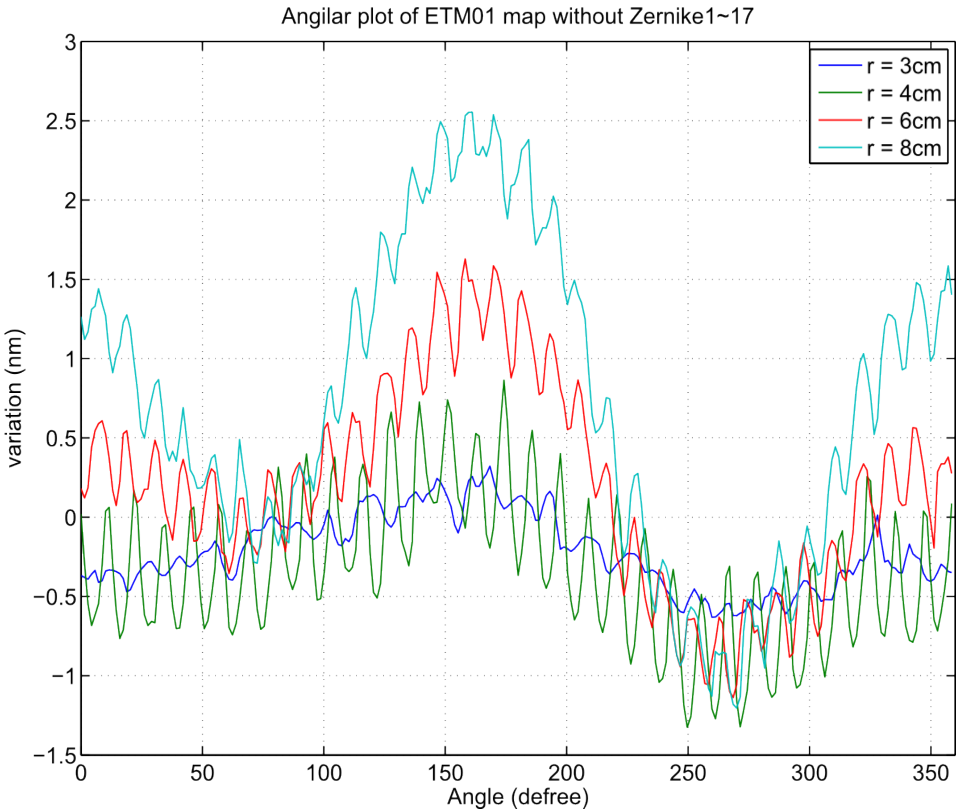
- Extremely good uniformity
  0.7 nm RMS over 6 µm of coating



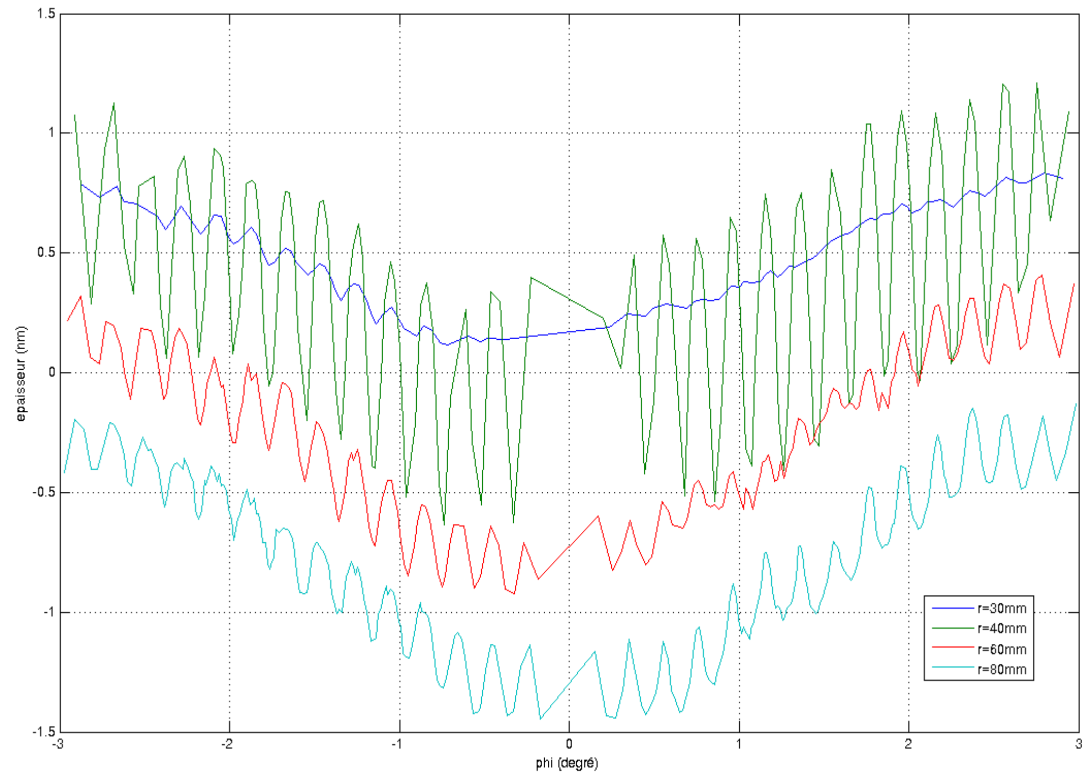
Original map over 160 mm without curvature

A close look at the coating

- Presence of ripple of amplitude 1 nm
- Expected and reproduced by the simulation



Measured ripple amplitude

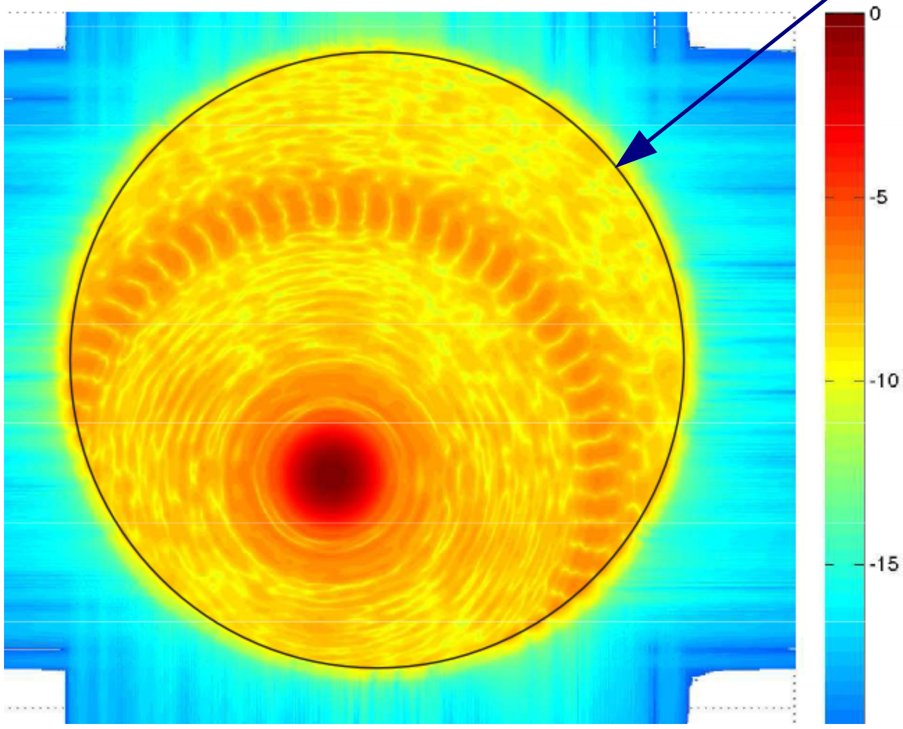


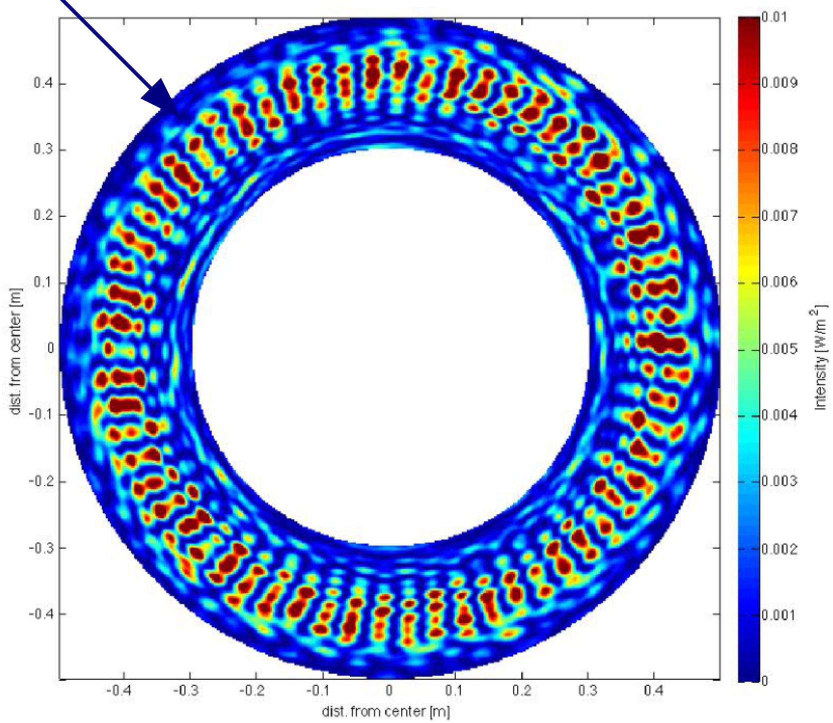
Simulated ripple amplitude

Effect of the ripples

- Still very good round trip loss ~ 20 ppm (budget 50 ppm)
- Ripples scattered light in a ring fashion
- Baffles essential to block the scattered light

Baffles





Advanced LIGO case (off centered baffles)

Advanced Virgo case

The coating now, it is:

For the end mirrors: 4 mirrors delivered to ALIGO
What can we say after the characterization ?

- RoC change: -9 m (more concave)
- Absorption: 0.32 ppm ± 0.06
- Mean diffusion: 5 ppm ± 2
- Transmission: 4 ppm (all 4 mirrors within 6%)
- Flatness: 0.71 nm RMS ± 0.04

(Value given on the central diameter of 160mm)

III

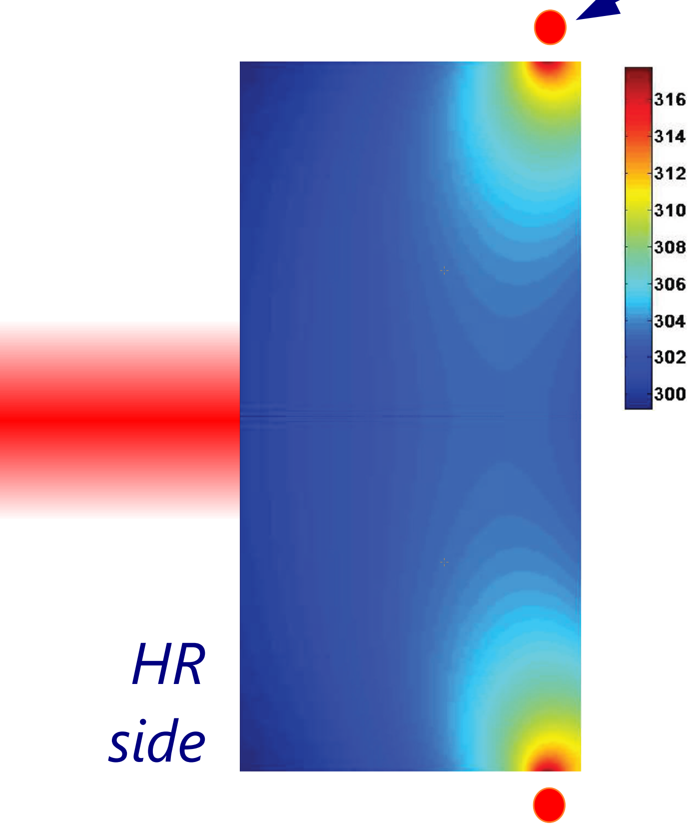
The planned in-situ tuning of the wavefront distortions

Effect of HR absorption and its compensation

HR absorption = change of RoC (tens of meter)

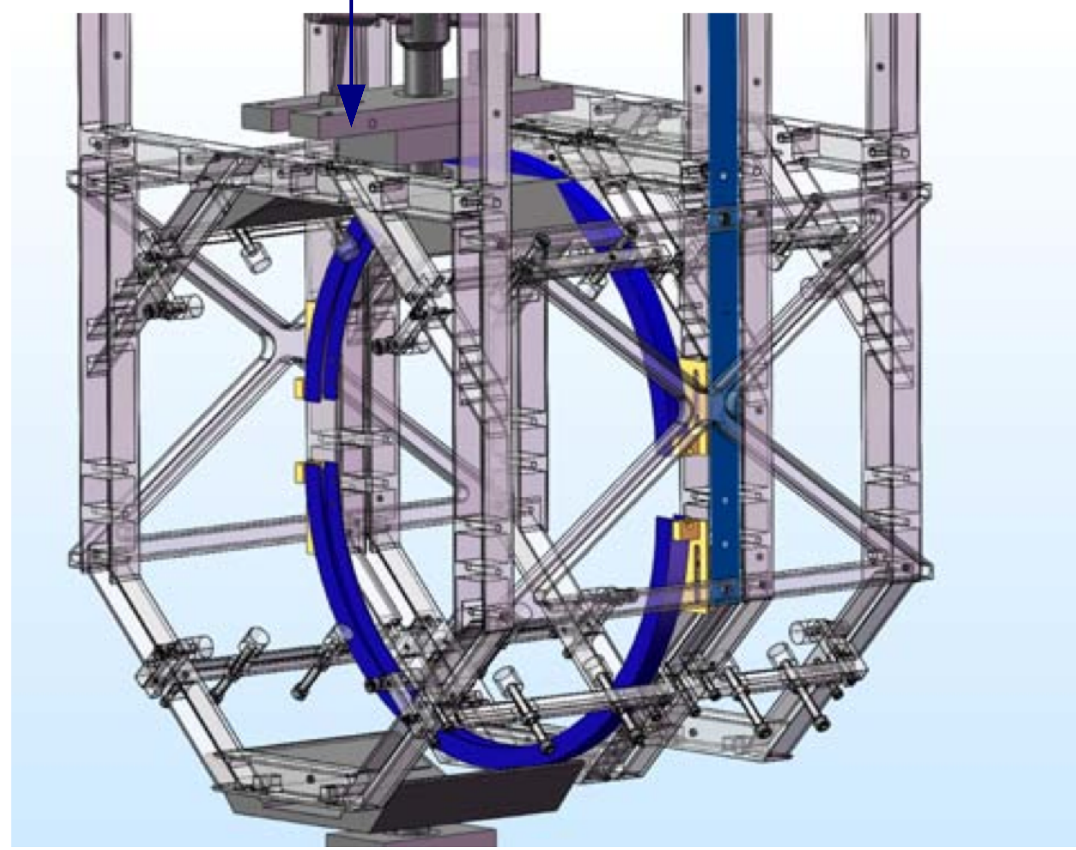
Use annular ring to tune and restore the RoC

heating ring



HR side

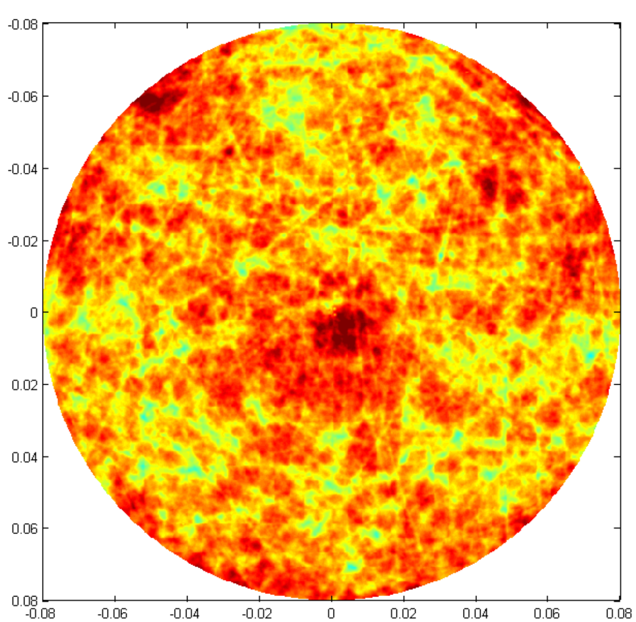
20W heating power



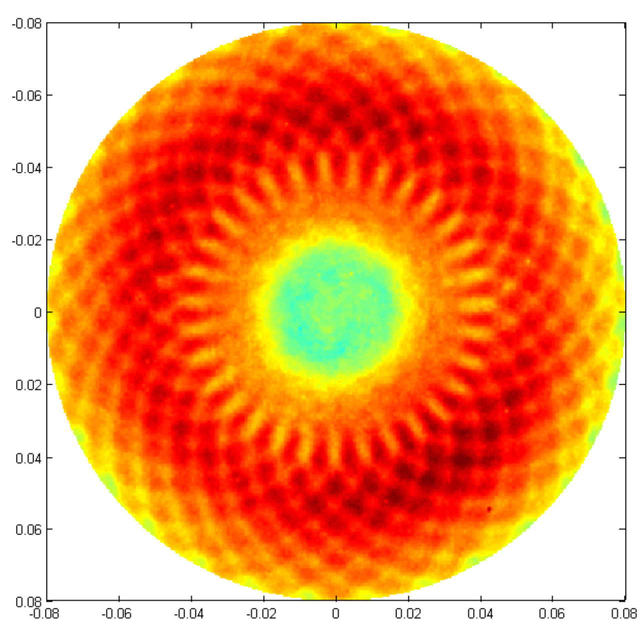
Perfect compensation ?

Compensation very good despite the difference sources of heating (Gaussian beam vs heating ring)

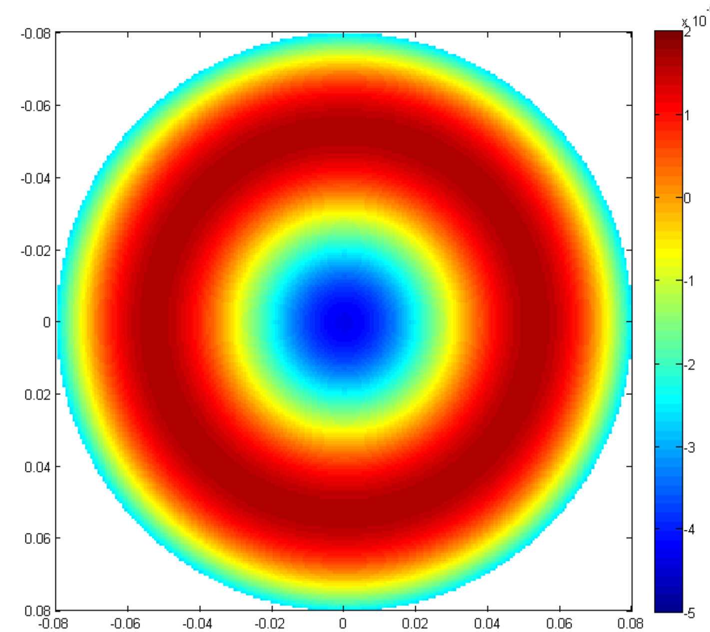
Comparison of different defects (color scale PV = 7 nm)



After polishing

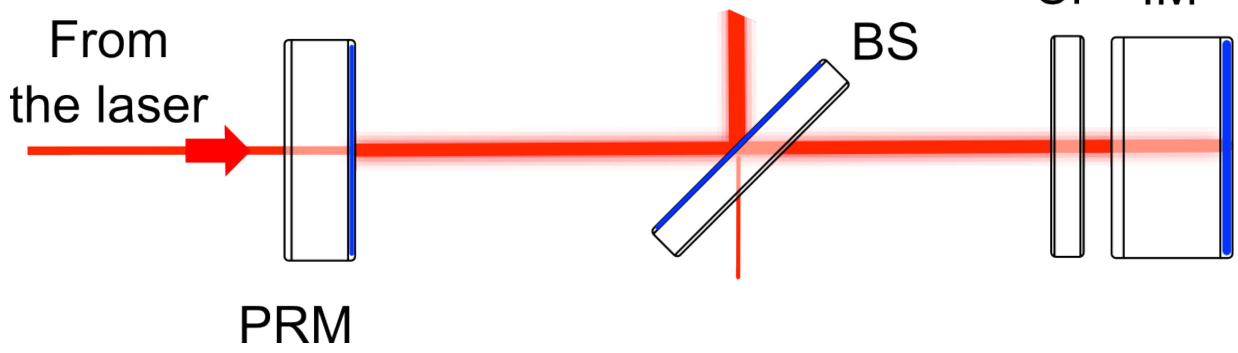


After coating



After TCS
(full power in the arms)

The recycling cavities



A lot of aberrations are collected in the recycling cavities:

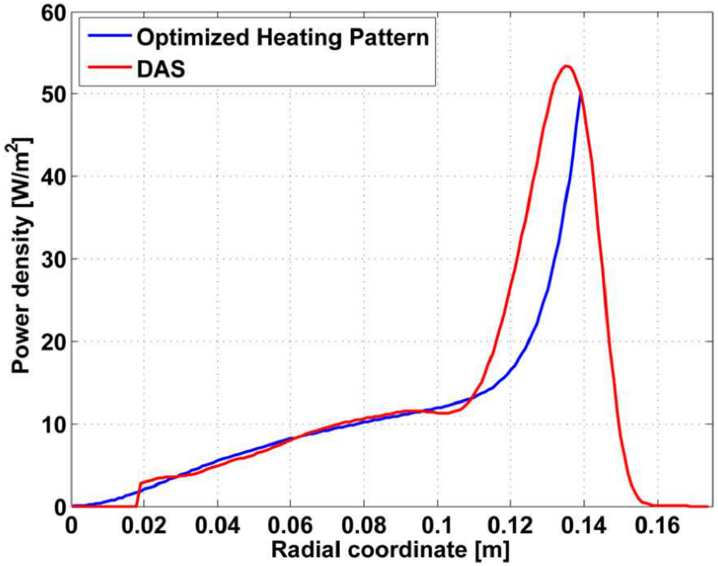
- Influence of substrate inhomogeneity (optic in transmission)
- Numerous surfaces and the tilted BS
- Main thermal effect from HR IM

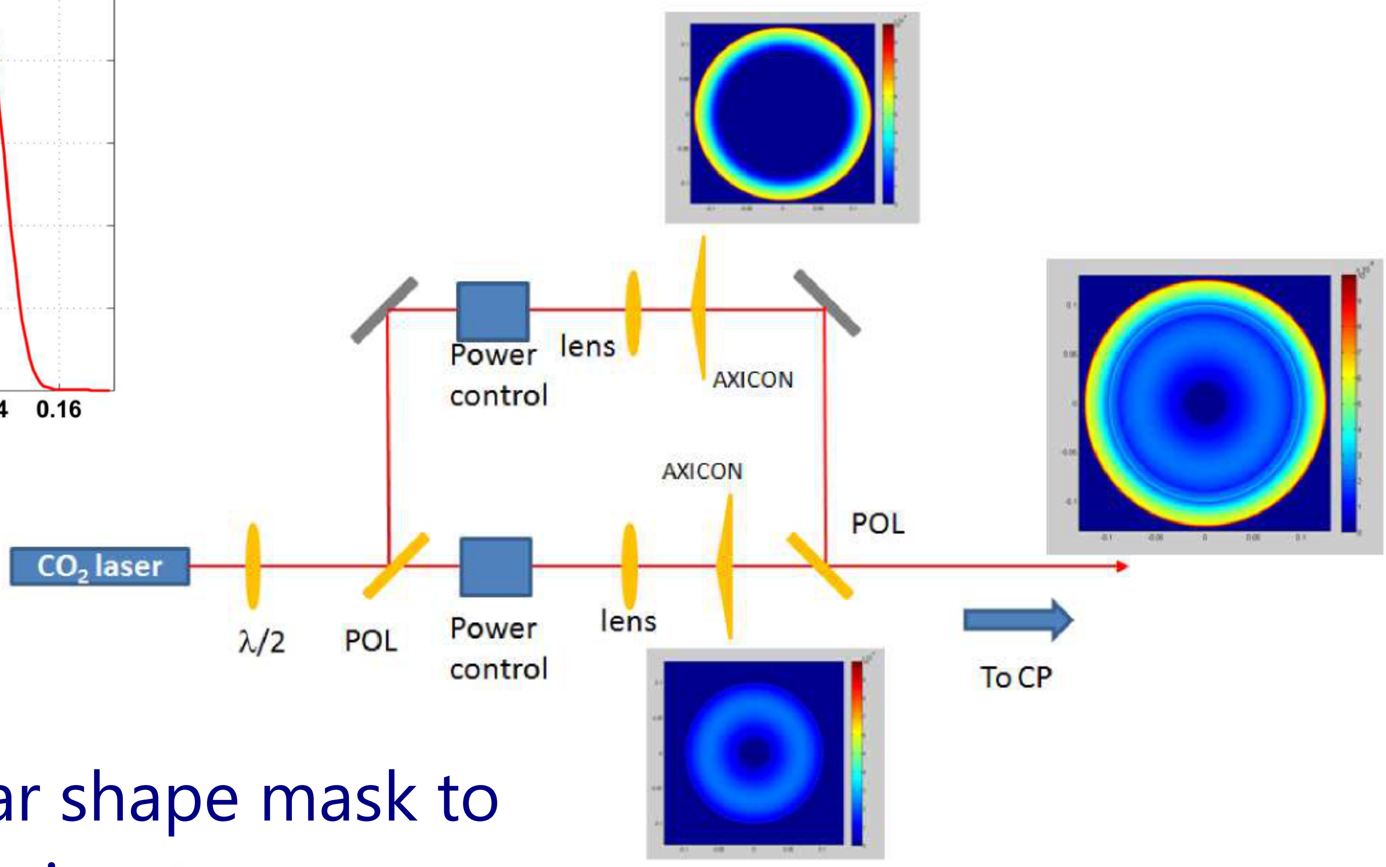
Sensitivity to aberration greatly depends on the recycling cavities design (marginally stable or not)

An extra optic dedicated to wavefront correction:
the Compensation Plate (CP)

The CO_2 laser compensation

- Principle demonstrated in the first generation
- Carefully designed heating pattern on the CP



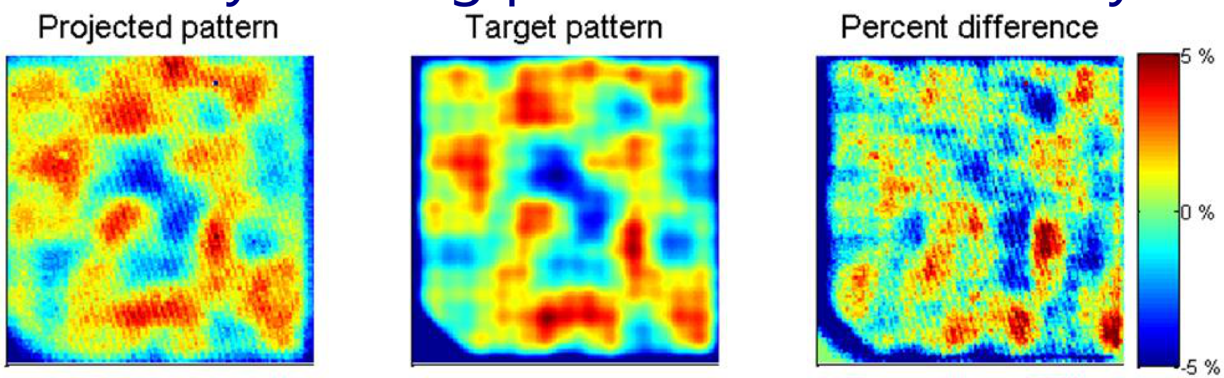


Advanced LIGO: star shape mask to create the right heating pattern

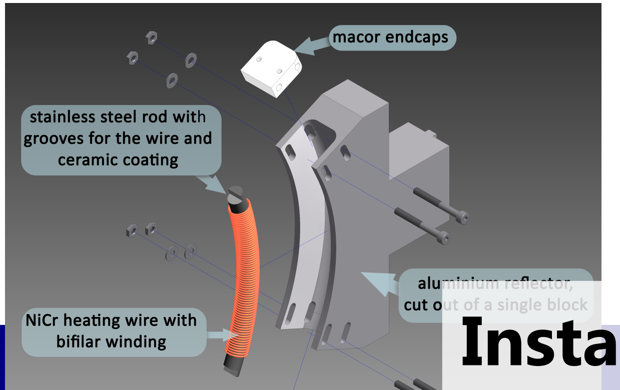
Extra compensation

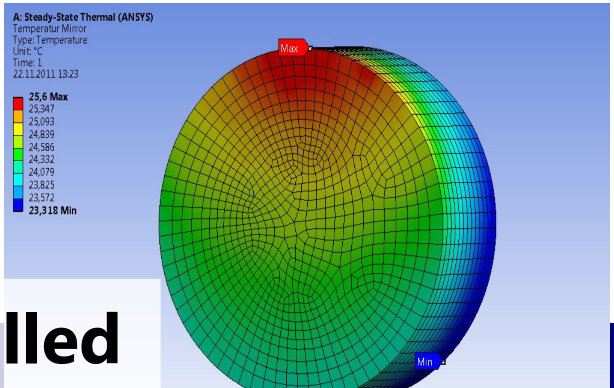
Advanced Virgo

- Heating ring also on recycling mirrors
  - HR can only tune the RoC in one direction → pre-curved optics
- Scanning heating beam
  - Arbitrary heating pattern for non axis-symmetric compensation

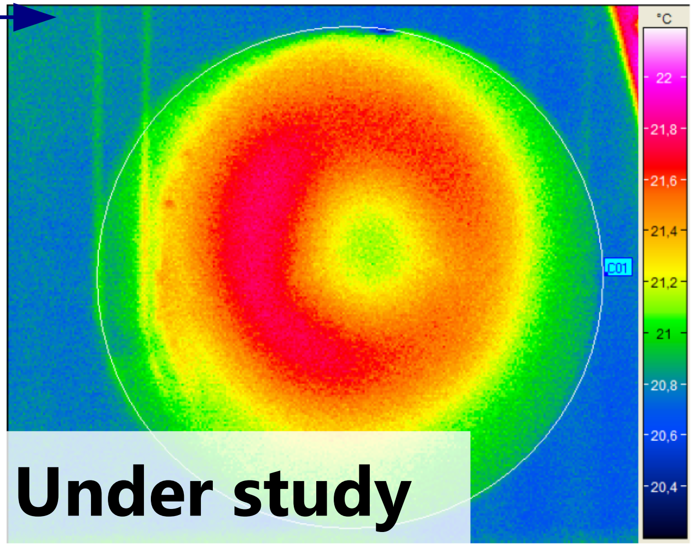


- Beam splitter thermal compensation →
- Astigmatism compensation:





Installed

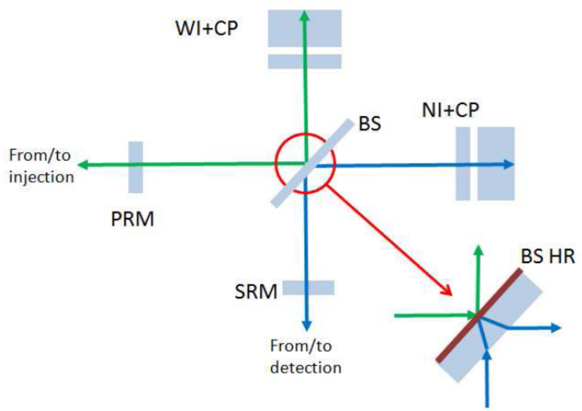


Under study

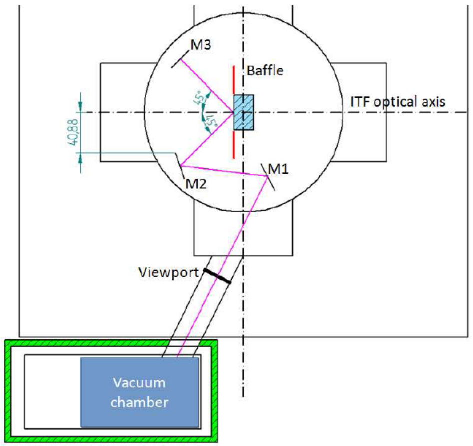
Know your enemies

- Actuation only works with reliable error signals
- Complex wavefront sensing:

Phase camera



Hartman wavefront sensing



HR surface sensing

To quantify the cold defects

To measure changes in the wavefront (due to absorption)

Complex strategy from the sensor measurement to the actuators error signals.

IV

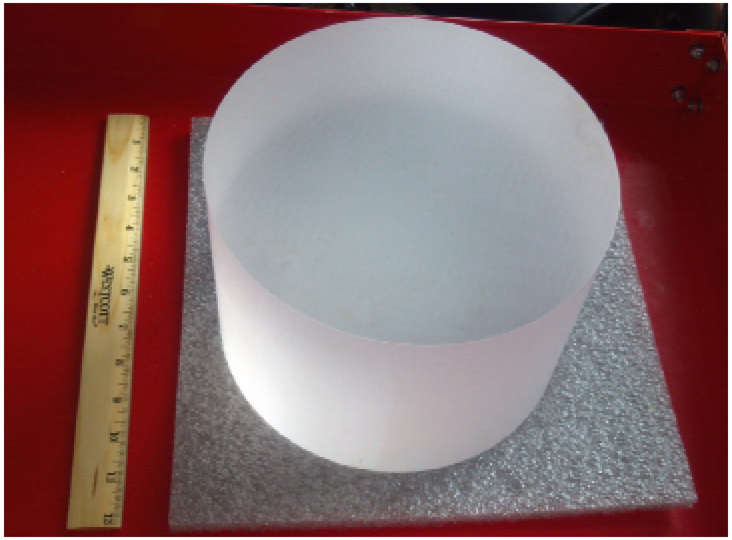
What to expect for the third generation

The cool interferometer

Potential substrate materials (sapphire, silicon) have very high thermal conductivity at cryogenic temperature:

- No wavefront distortions due to the absorption
- No possibility of thermal actuation

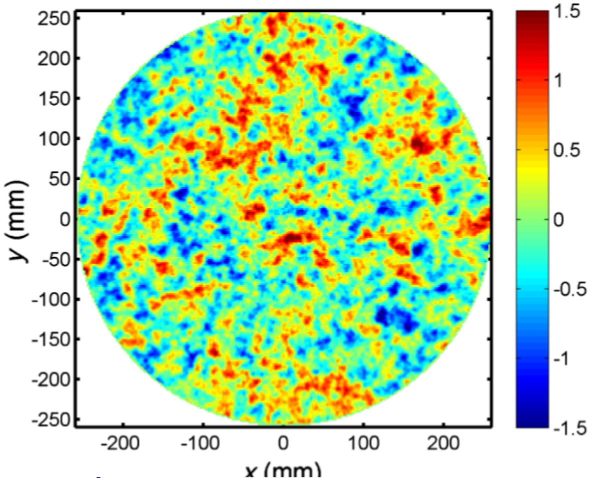
Potential difficulties with sapphire since it is hard to polish and maybe non uniform.
The interferometer must be robust to aberration.



Sapphire substrate

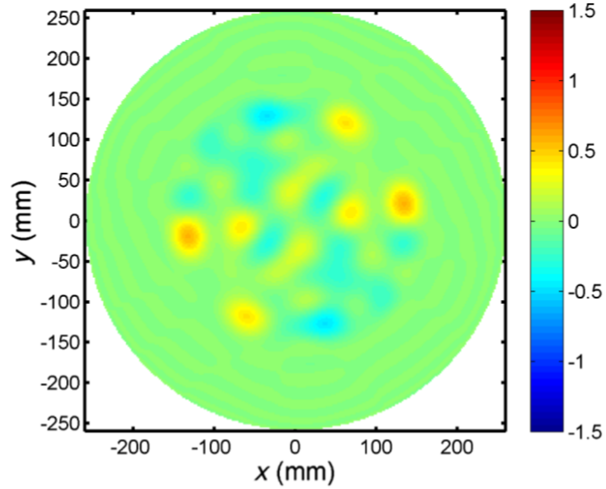
Advanced in situ correction

Tuning of the mirror surface by heat:

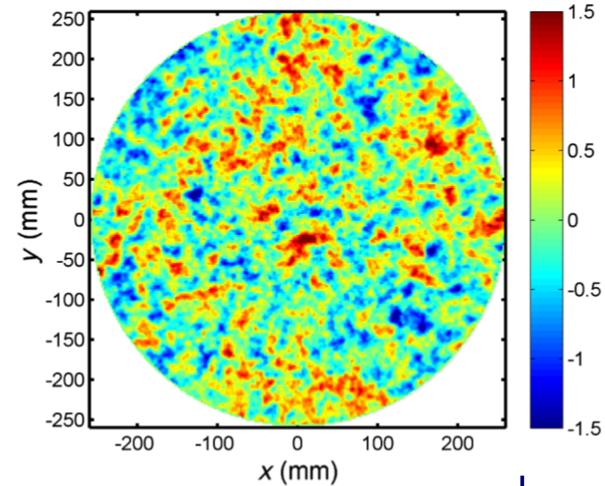


Original map

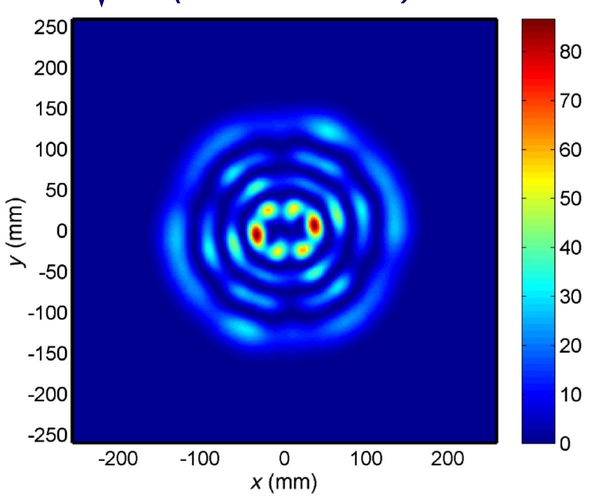
(0.5 nm RMS)



difference

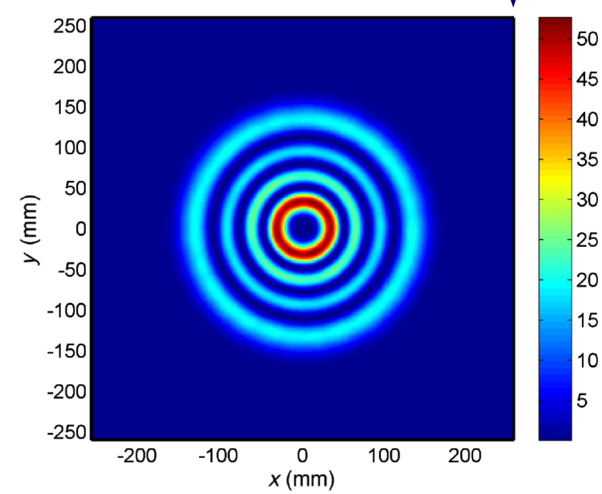


Corrected map



No need to correct all the surface!

Actuation and error signals theoretically derived



Conclusion

Aberration and its compensation are taken into account from the start of the interferometer.

Substantial increase in the metrology and simulations firepower in the recent years.

Getting toward the in situ correction for all sources of distortions.

Conclusion

	Arm cavities		Recycling cavities	
	RoC correction	Arbitrary correction	lens correction	Arbitrary correction
First generation	Exceptional	None	First order	None
Second generation	Systematic	None	Flat wavefront	For Advanced Virgo
Third generation[1]	Systematic	Likely	Even better	Likely

[1] room temperature interferometers

Sources and credit

Title slide photos
- left: ALIGO TM surface
- middle: picture made in LMA
- right: AVIRGO TCS, VIR-0352A-12

Slide 5
- Thermal correction of the radii of curvature of mirrors for GEO 600 http://stacks.iop.org/0264-9381/21/i=5/a=090
- And the corresponding Amaldi 3 poster

Slide 6
- Central heating radius of curvature correction (CHRoCC) for use in large scale gravitational wave http://stacks.iop.org/0264-9381/30/i=5/a=055017

Slide 7
- TCS scheme from LIGO DCC: G070643-00

Slide 8
- Sidebands gain Virgo TDS: VIR-0230A-11
- Arm cavities RTL as a function of CHRoCC temperature, logbook post 290025

Slide 10
- ALIGO noise budget: http://stacks.iop.org/0264-9381/27/i=8/a=084006
- Avirgo noise budget: https://tds.ego-gw.it/ql/?c=8940

Sources and credit

Slide 12
- Initial Virgo mirror spec: https://tds.ego-gw.it/ql/?c=7457
- Advanced Virgo mirror spec: from the call for tender\

Slide 14
- Maps from ITM04, cutting frequency between low and high frequency = 50 m^-1

Slide 15
- RoC data from G1200565-v1 at GWADW 12
- Data from the Caltech measurement available on the DCC
- RTL simulations from VIR-0632A-10

Slide 16
- Photos taken at LMA in the coating chamber

Slide 17
- ETM07 after coating, data taken at Caltech LIGO DCC E1300365-v1

Slide 18
- ETM01 ripples from LIGO DCC T1300045-v4
- Ripples simulations from LMA logbook

Slide 19
- ALIGO ripples simulation: DCC G1300398 & T1300354
- AVirgo ripples simulation: VIR-0137A-13

Sources and credit

Slide 20

- Data from the LMA reports for delivery of the Advanced LIGO mirrors

Slide 22

- Temperature distribution from Advanced Virgo Technical Design report
- Details of the heating ring from VIR-0352A-12
- Heating ring inside the mechanical ALIGO structure: G1201041-v2

Slide 23

- ETM mirror surface measured by Tinsley
- ETM mirror coating measured by Caltech
- HR surface after compensation, data from A. Brooks (seen in G1201041-v2)

Slide 25

- Drawing found in the Advanced Virgo Technical Design report (TCS chapter)

Slide 26

- TCS arbitrary heating pattern from: VIR-0164A-13
- Compensation of thermal lensing in the GEO600 beamsplitter. Thesis from H. Wittel
- Astigmatism compensation, GEO-HF logbook p2208, p4001, p4094

Slide 27

- Drawing/photos found in the Advanced Virgo Technical Design report (TCS chapter)

Sources and credit

Slide 29

- Sapphire picture from “KAGRA” Status by S. Miyoki 11/09/2012

Slide 30

- “Reduction of higher order mode generation in large scale gravitational wave interferometers by central heating residual aberration correction”, Phys. Rev. D 87, 082003, http://link.aps.org/doi/10.1103/PhysRevD.87.082003
- “Adaptive optics techniques to correct aberrations in gravitational wave interferometers operating with Laguerre-Gauss high order modes”, G. Vajente R. Day to be submitted