Advanced Virgo:

High power operations
Thermal aberrations, figure errors and compensations

Gabriele Vajente*
on behalf of the Virgo Collaboration
INFN sezione di Pisa

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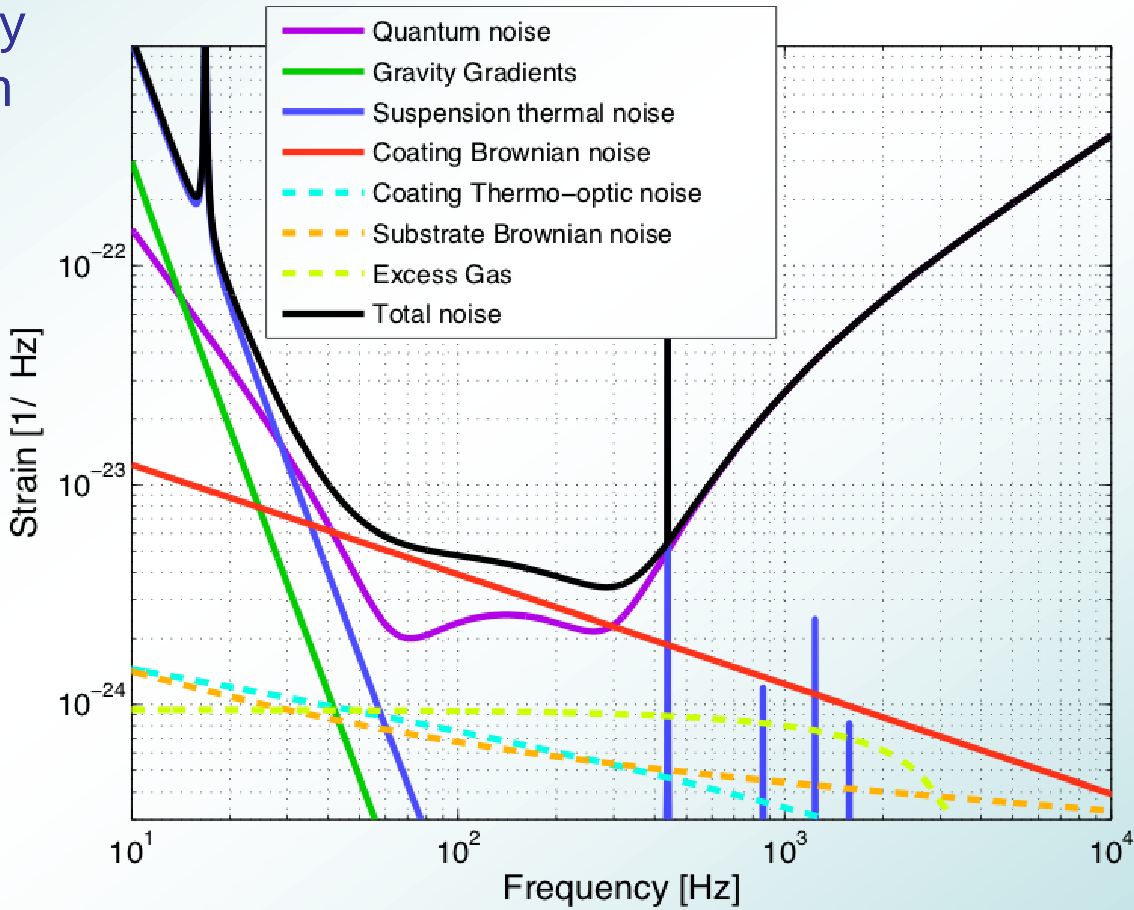
Outline of the talk

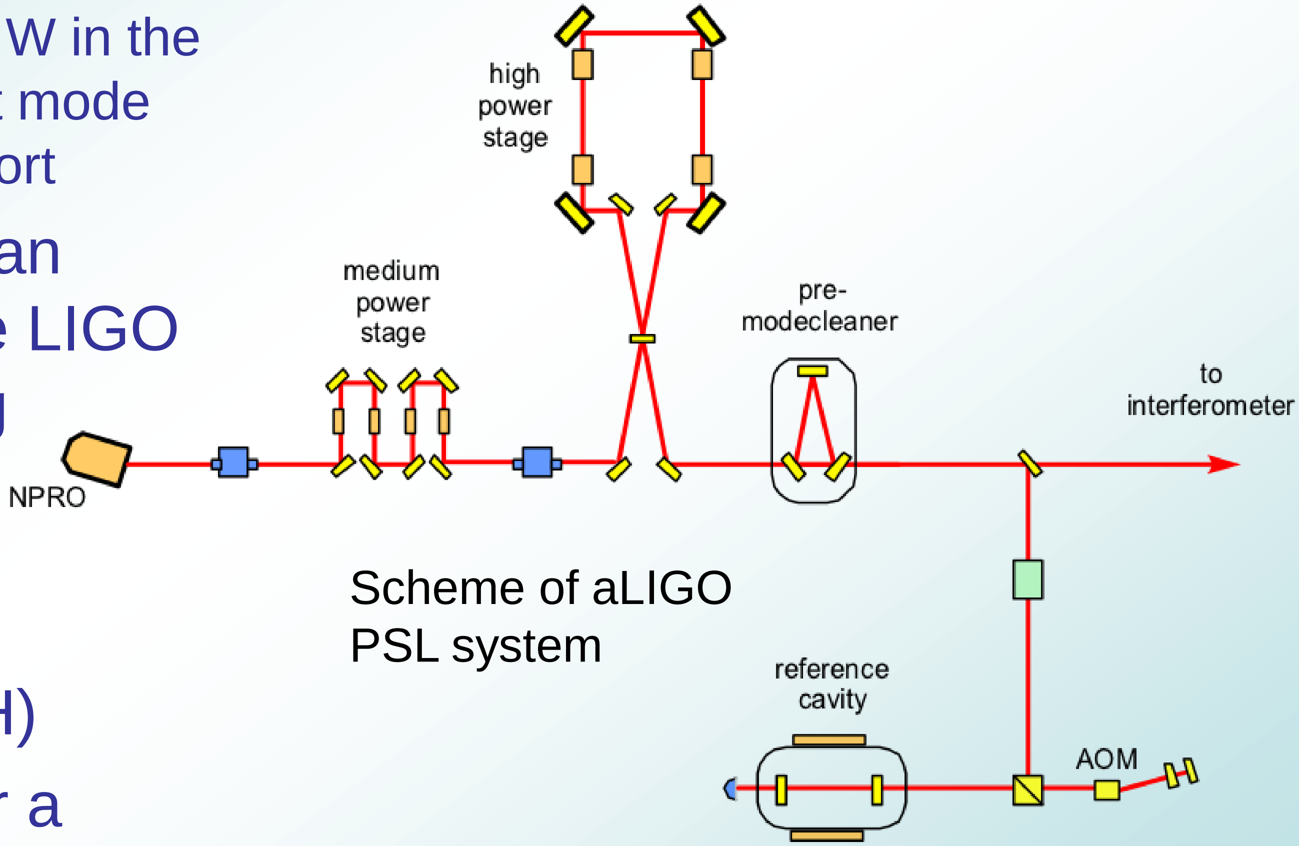
- To improve the high frequency sensitivity (shot noise) we can
  - Increase the input power
  - Inject squeezed light *(but this is outside the scope of this talk)*
- High power operation needs high power laser
- Choice of recycling cavity configuration (aLIGO stable AdV marginally stable)
- Highlights on optical simulation, development and results
- Focus on marginally stable cavities
  - Effect of optical path distortions
  - Sensing and compensation strategy



HIGH POWER SOURCES

High power operations

- Need to inject more than 100 W in the Gaussian mode into the interferometer
  - About 165-175 W in the TEM00 at input mode cleaner entry port
- aLIGO will use an extension of the LIGO scheme, adding a high-power stage to the medium (35W) power one (LZH)
- AdV is going for a "single stage" solution

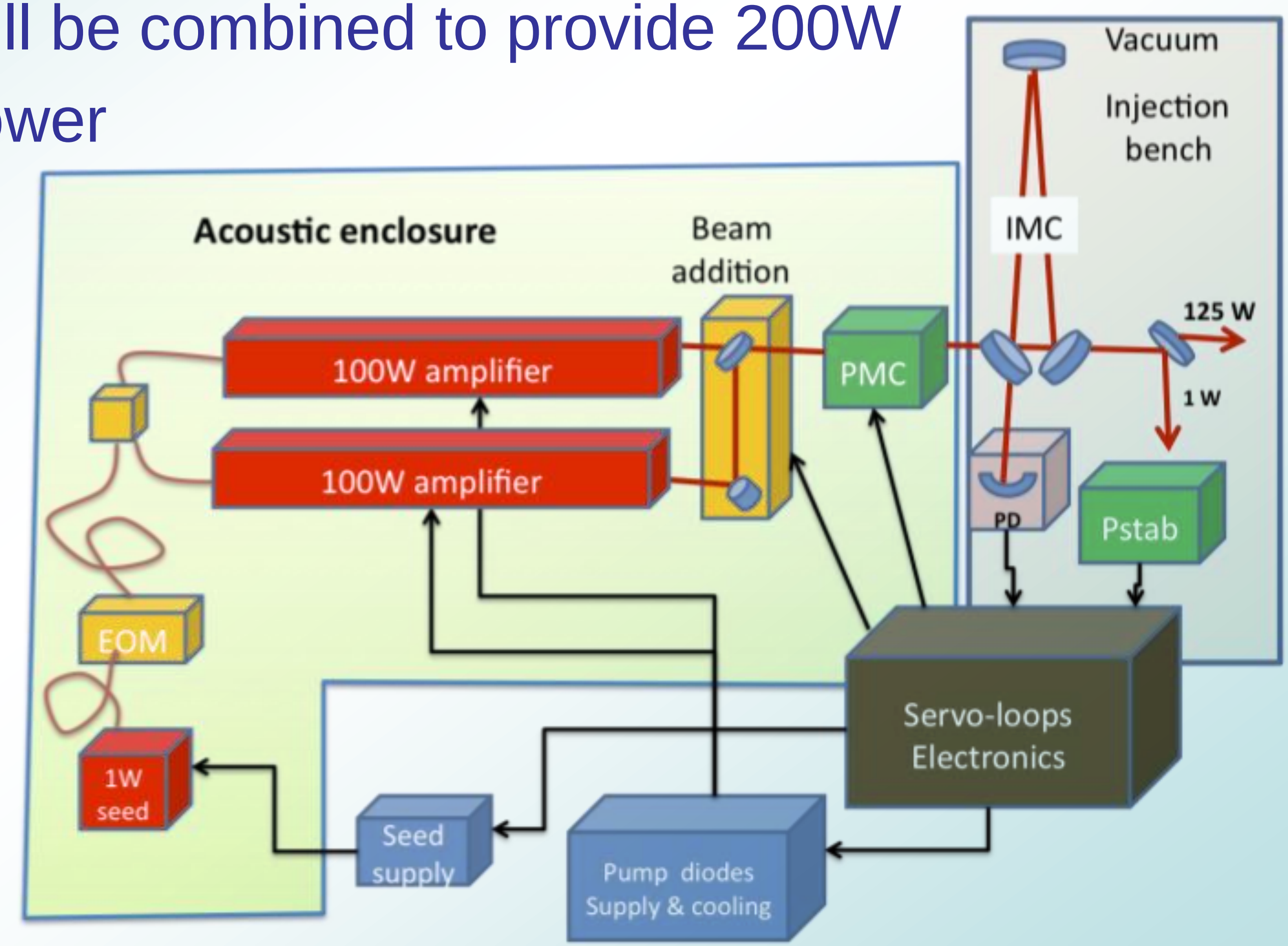


Scheme of aLIGO PSL system

Advanced LIGO Ref. Design LIGO-M060056-v2 (March 2011)

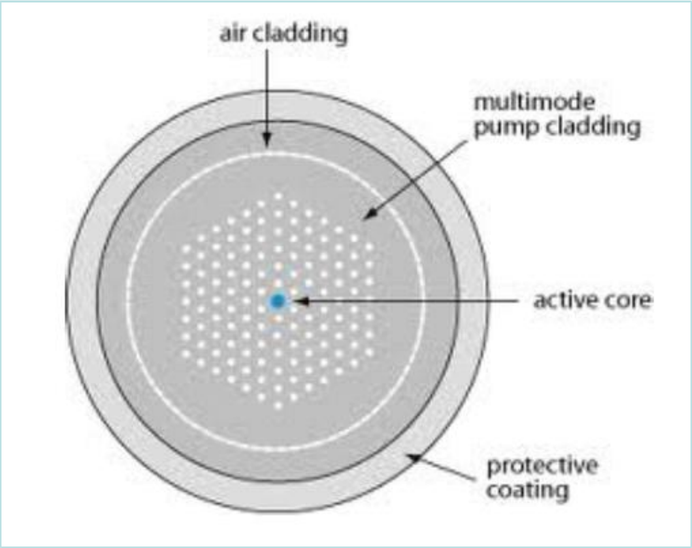
AdV rod-fiber amplifier

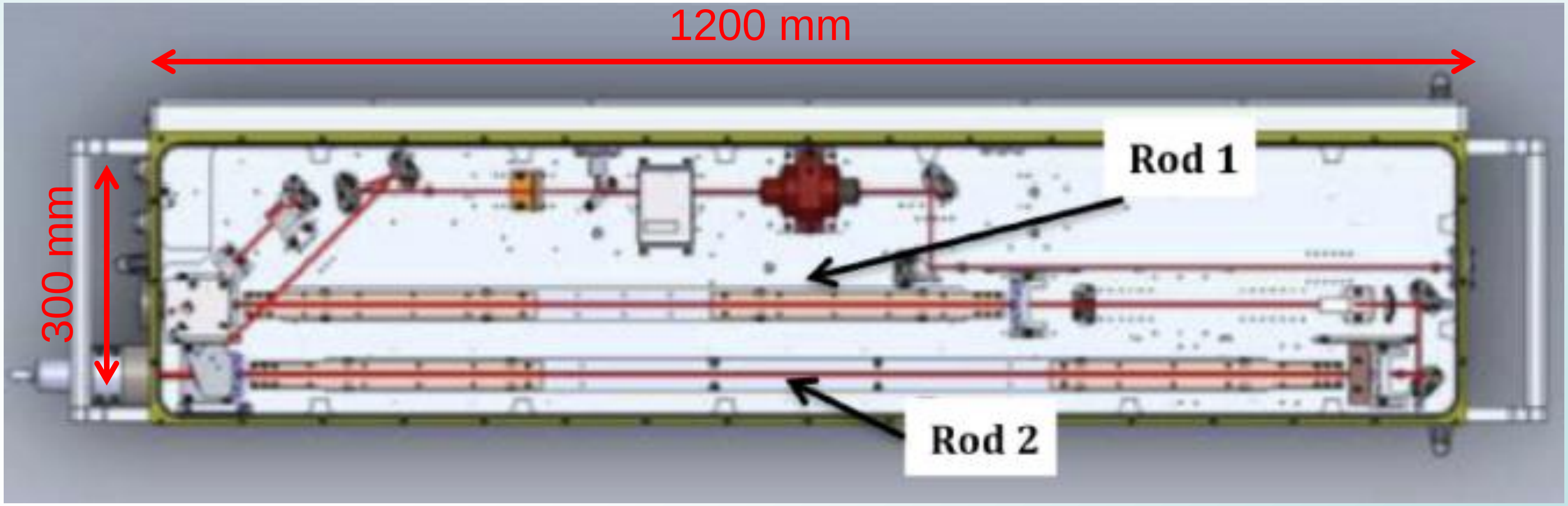
- 1 W Nd-YAG seed laser (Innolight) is amplified by two 100W rod-type fiber amplifier (Eolite) in parallel
- The two beams will be combined to provide 200W
- Frequency and power stabilization loops are very similar to the Virgo and LIGO ones



100 W prototype

- Amplification from 300mW seed to 100W output obtained with two rod-type fiber stages (750 and 1080 mm long)

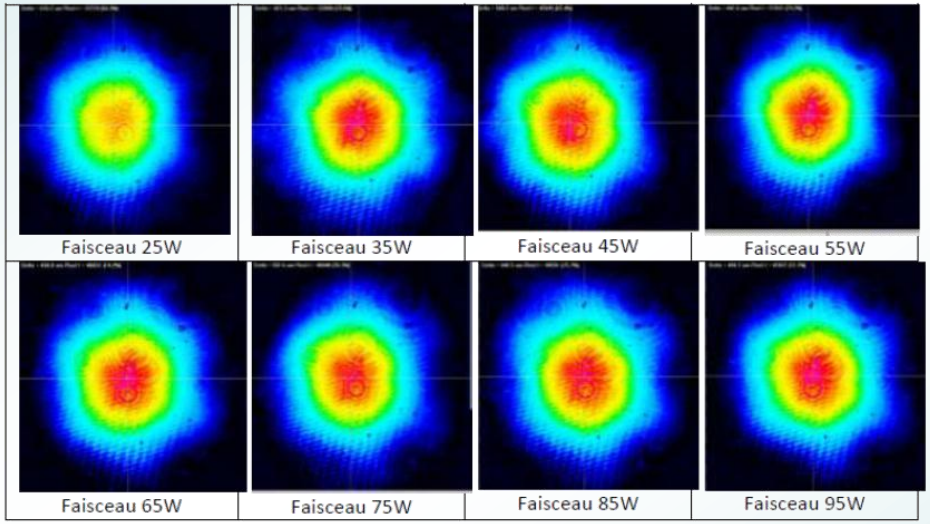


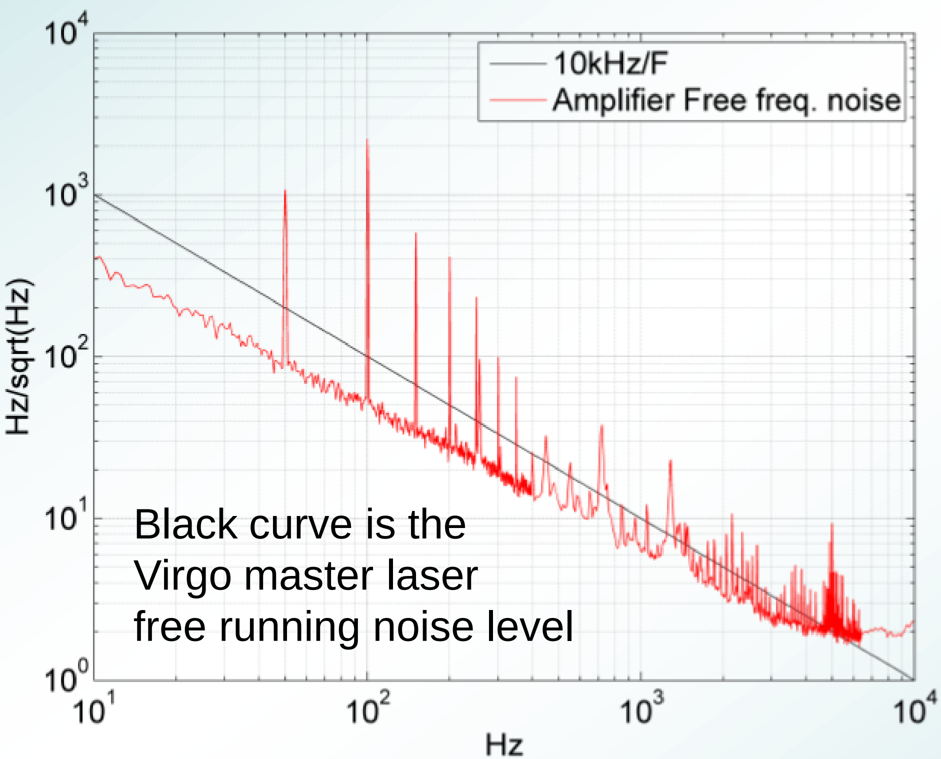


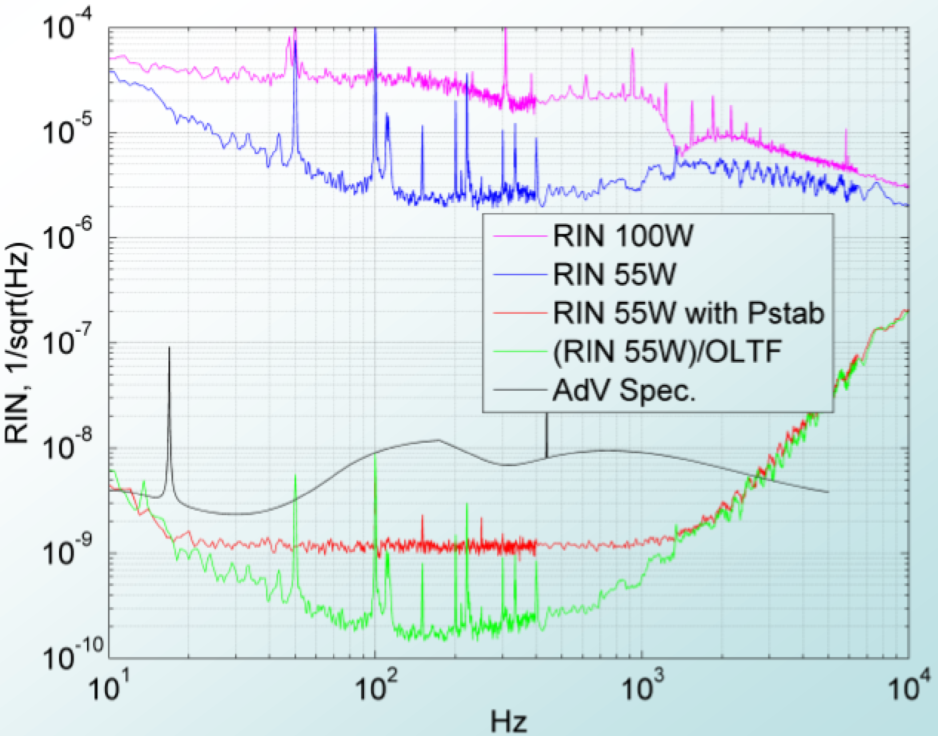
Performances

- Tests performed at Nice and Eolite for beam shape and noise level are promising

AdV Technical Design Report VIR-0128A-12 (April 2012)







RECYCLING CAVITIES:
SIMULATION AND COMPENSATION

Advanced detector configurations

Very sensitive to defects

Simpler core optical system

More complex in/out optics

Simpler mechanical system (for Virgo, having the super-attenuator already working)

Simpler control scheme

Longer experience

Heavier load on TCS

More robust against defects

Recycling cavity optical configuration is more complex

The recycling cavity includes the in/out telescope

Increased mechanical and control complexity

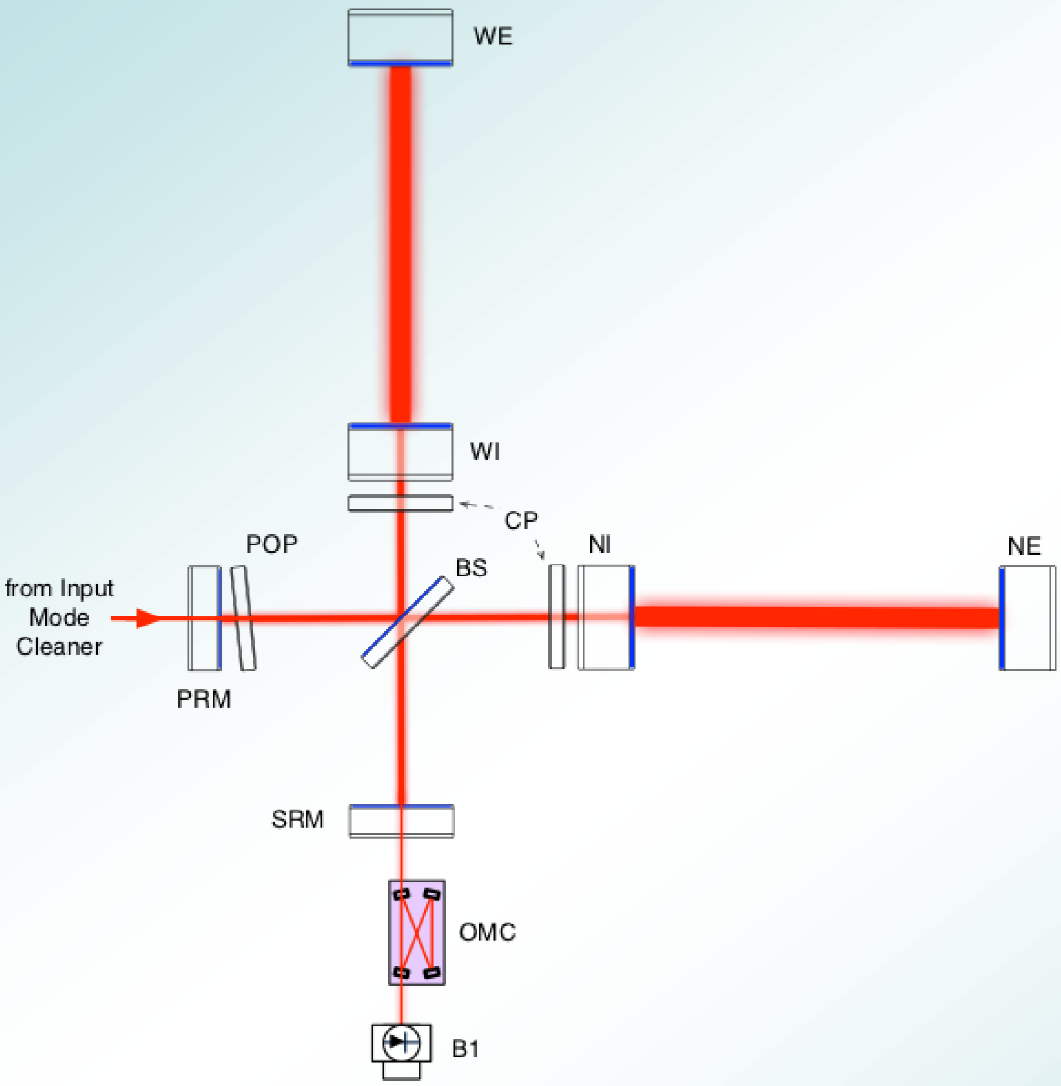
Need to control lateral motions of rec. cavity mirrors

Advanced detectors will operate at high power (>600kW in the arms)

Experience from LIGO and Virgo underlined the importance of thermal effects

We have then learned, mainly using simulations, that also "cold" mirror defects are crucial

AdV recycling cavity configuration



- PRC and SRC are marginally stable (meaning high order modes are partially degenerate with the fundamental one)
- Configuration conceptually similar to the Virgo one
- The simplest one to implement from the point of view of mechanics and optics

Simulation tools

- MSRC are **very sensitive to all defects** inside recycling cavities
  - Thermally induced deformations (both surface and refractive index changes)
  - Cold defects (surface errors, transmission inhomogeneities)
- Design and tolerancing is strongly based on reliable simulaton tools

Modal simulations	FFT simulations
The laser field is described as an expansion in an orthonormal basis of Gaussian modes.	The laser field is described as an image of the transverse amplitude and phase distribution, sampled at an evenly spaced grid.
Pretty fast, but convergence of results gets critical in MSRC when large defects are present	Quite slow, but the only tool to give accurate results for MSRC in presence of defects
Very versatile, since tools exists that allow simulation of almost any optical system	So far only fixed configuration possible. But FOG is opening new windows (see later and R.Day's talk)

AdV will go for MSRC…

- Need to develop detailed FFT simulations of the entire interferometer:
  - Evaluation of the impact of secondary beam extraction strategies
  - Evaluation of the impact of thermal effects, including non axisymmetric ones, inside the recycling cavities
  - Evaluation of the impact of surface and transmission defects inside the recycling cavities
- FFT codes
  - **SIS** is able to simulate only a double cavity (LIGO-G070659-00-E)
  - **OSCAR** simulated Fabry-Perot cavities or central interferometer (dual recycled Michelson) (J.Phys.Conf.Series 228, 012021)
  - **DarkF** can simulate full dual recycled Advanced Virgo (VIR-0007A-08)
  - **FOG** can simulated full dual recycled Advanced Virgo and arbitrary configuration (see R.Day's talk)

Optical path length distortion - SB

- Any defect inside the recycling cavity will induce a distortion of the wavefront
- Figure of merit: **optical path length distortion weighted with the beam power**
- Sideband recycling gain is affected

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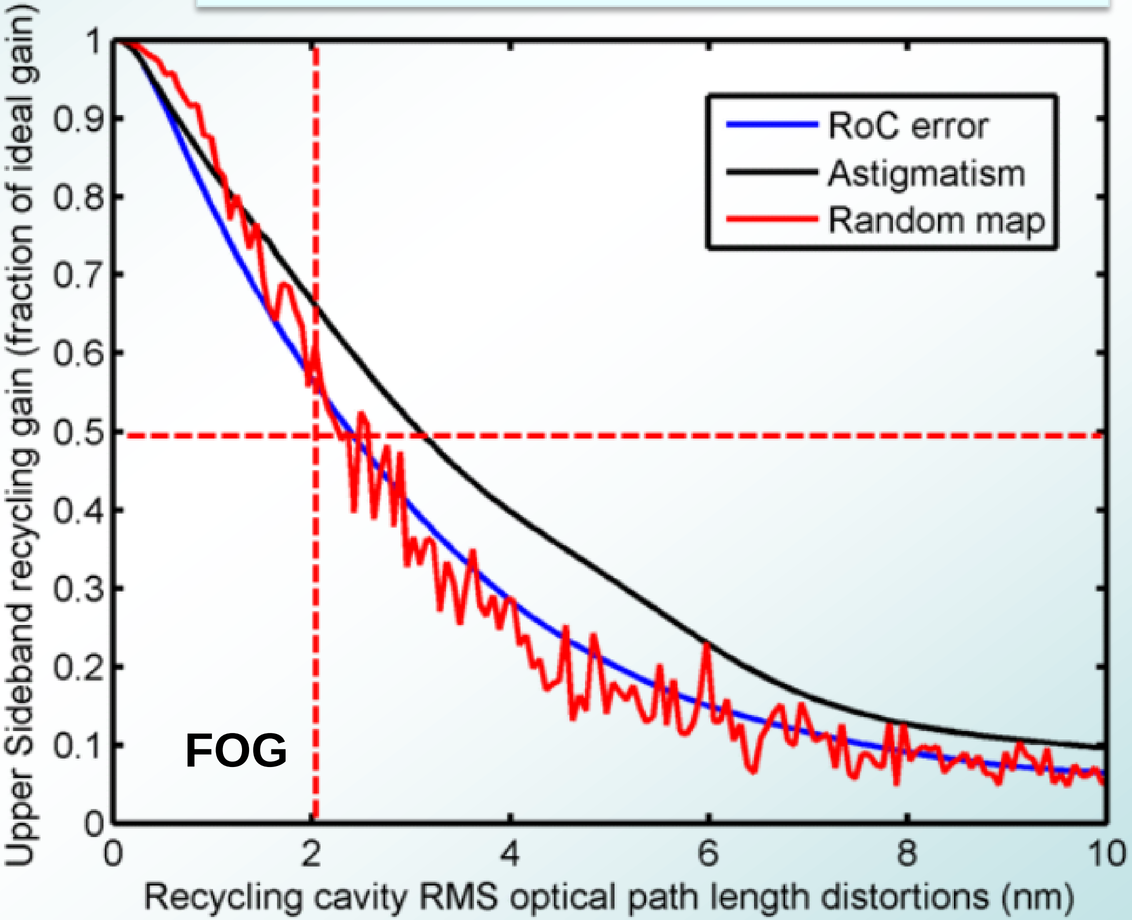
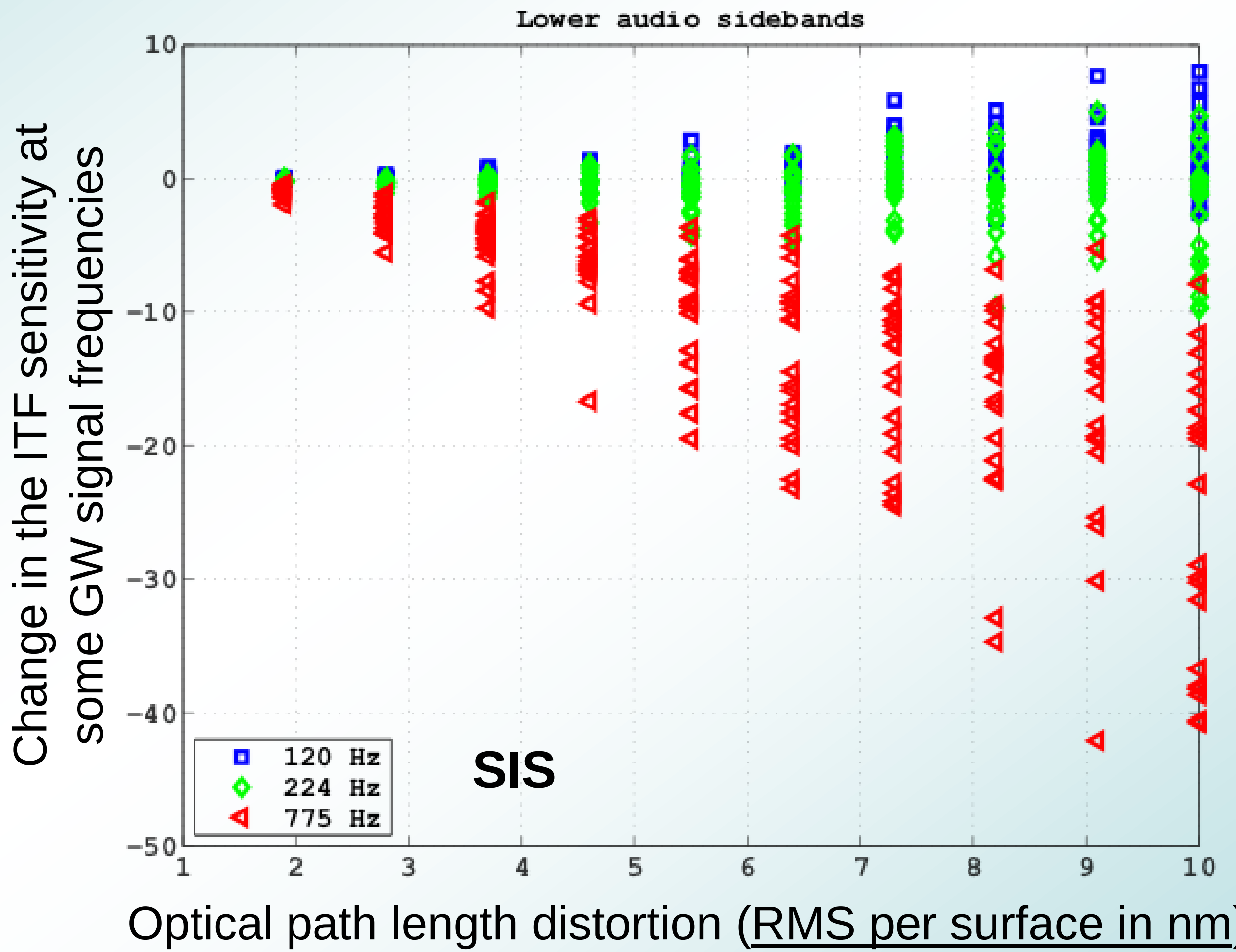


Requirement: SB gain at least 50% of ideal
Corresponds to 2 nm RMS total error

Optical path length distortion - GW

- Effect on audio sidebands and detector sensitivity
- Simulated with SIS: one arm cavity coupled to a signal recycling cavity
- Each point correspond to a different random map with the given RMS
- **2 nm RMS corresponds to 2% change**



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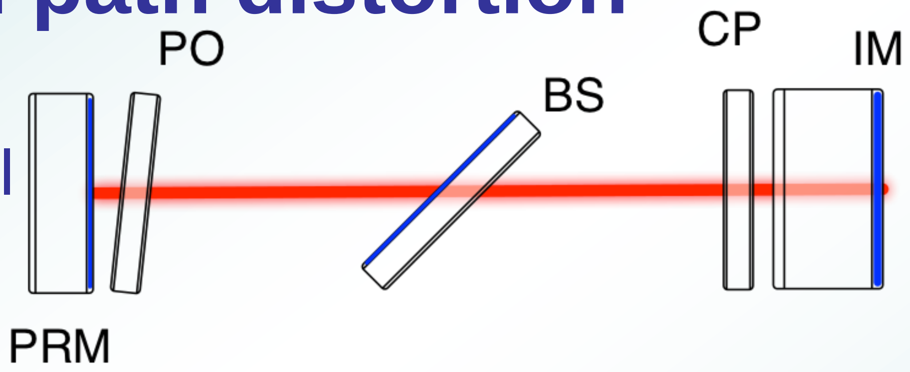
VIR-0326A-11 (May 2011)

Origin of optical path distortion



- Surface figure errors. Spatial frequencies below 50 m^{-1} are the most important
  - Standard polishing gives surfaces with about 2 nm RMS
  - Corrective coating gives 0.5 nm RMS
- Substrate index inhomogeneities (specifications 2.5 ppm over 200 mm and 0.5 ppm over 100 mm diameters)
  - For 20 cm thick optics gives significant distortions (measured between 3 and 6 nm RMS on Advanced LIGO optics)
- Distortion due to suspension system estimated to be negligible
  - ANSYS simulation gives 0.15 nm RMS from surface deformation and 0.1 nm RMS from photo-elastic effect

All these numbers are given after subtraction of piston, tilt and curvature

Total distortion and correction

- Sources are:
  - Power/Signal recycling mirror surface, pick-off plate transmission, beam splitter transmission and reflection, compensation plate transmission, input test masses transmission, input test masses reflection
- Subtraction of
  - **piston**
  - **tilt**
  - **radius of curvature errors**
- **Total RMS optical path distortion of the order of 10 nm RMS**
- Too large for proper ITF operations (would give SB gain at less than 10%)

Corrected by the longitudinal control system

Corrected by the angular control system

Compensated by symmetric thermal compensation system, and radius of curvature tuning systems like Ring Heater or CHRoCCs

Aberration reduction strategy

- Even in the "cold" state, without thermal load, the recycling cavity defects are too large for proper operation of the ITF
- TCS (thermal compensation system) must correct also these defects
- We are going in the direction of **adaptive optics**
  - **Instead of pushing for the best system out of the box (which might not be enough) we implement active systems to sense and correct defects**
- We need sensors for both the "cold state" defects and the thermally induced deformations
  - Phase cameras
  - Hartmann sensors

How to sense "cold state" defects?

- Hartmann sensors are very sensitive but can only measure changes in the wavefront: not suitable for cold defects
- **Phase cameras** allow measuring the intensity and phase of carrier and sidebands fields independently at ITF output ports
- Aberrations might be larger than PRC linewidth for sidebands (if finesse is 200, FWHM=1.3 nm)
- This explains why recycling cavities are so sensitive to aberrations
- The sideband field is resonant at different longitudinal position of the PRC
- The distortion can be measured using the phase difference between sideband and carrier fields

VIR-0389A-11 (July 2011)

Simulation results

- From PRC pick-off sideband phase (relative to carrier) one can measure the common mode optical path distortion (FFT simulations)

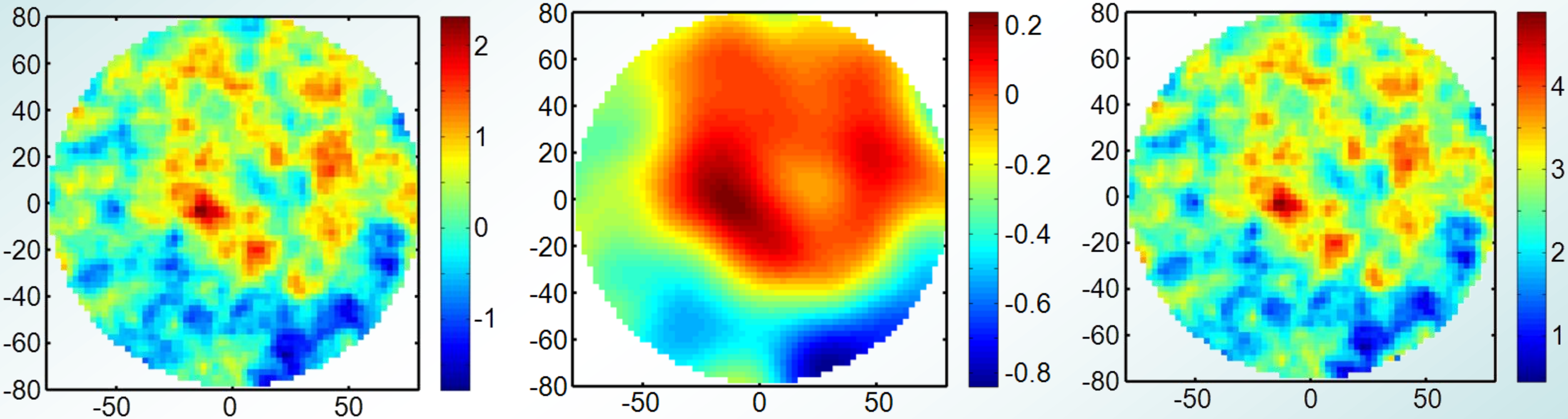


Figure 6.47: FOG simulation. Left: common aberration in recycling cavity (color scale in nm). Middle: phase difference between upper sideband and carrier (color scale in rad). Right: Resulting aberration map after filtering phase difference map (color scale in nm). Horizontal and vertical scales in mm.

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Simulation results

- From the dark fringe sideband amplitude image one can also get an information on the differential distortion
- Not a direct calibrated measurement of the OPL but a qualitative indication
  - But one can calibrate it applying a known deformation to the ITF

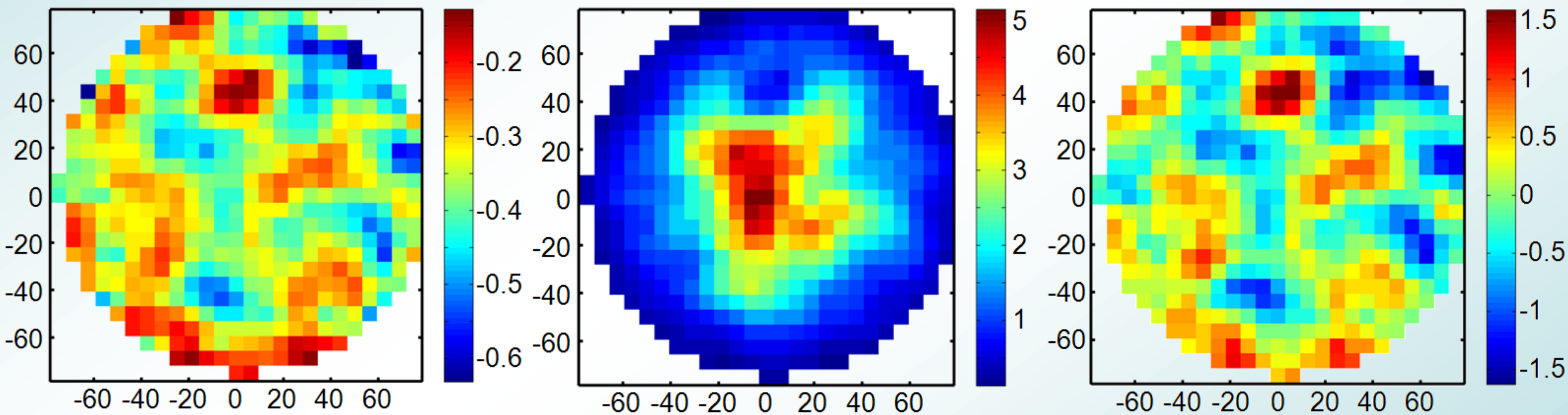

Figure 6.48: FOG simulation. Left: differential aberration in recycling cavity (color scale in m). Middle: lower sideband amplitude on dark fringe. Right: Difference between lower sideband and carrier amplitude normalized by carrier amplitude. Horizontal and vertical scales in mm.

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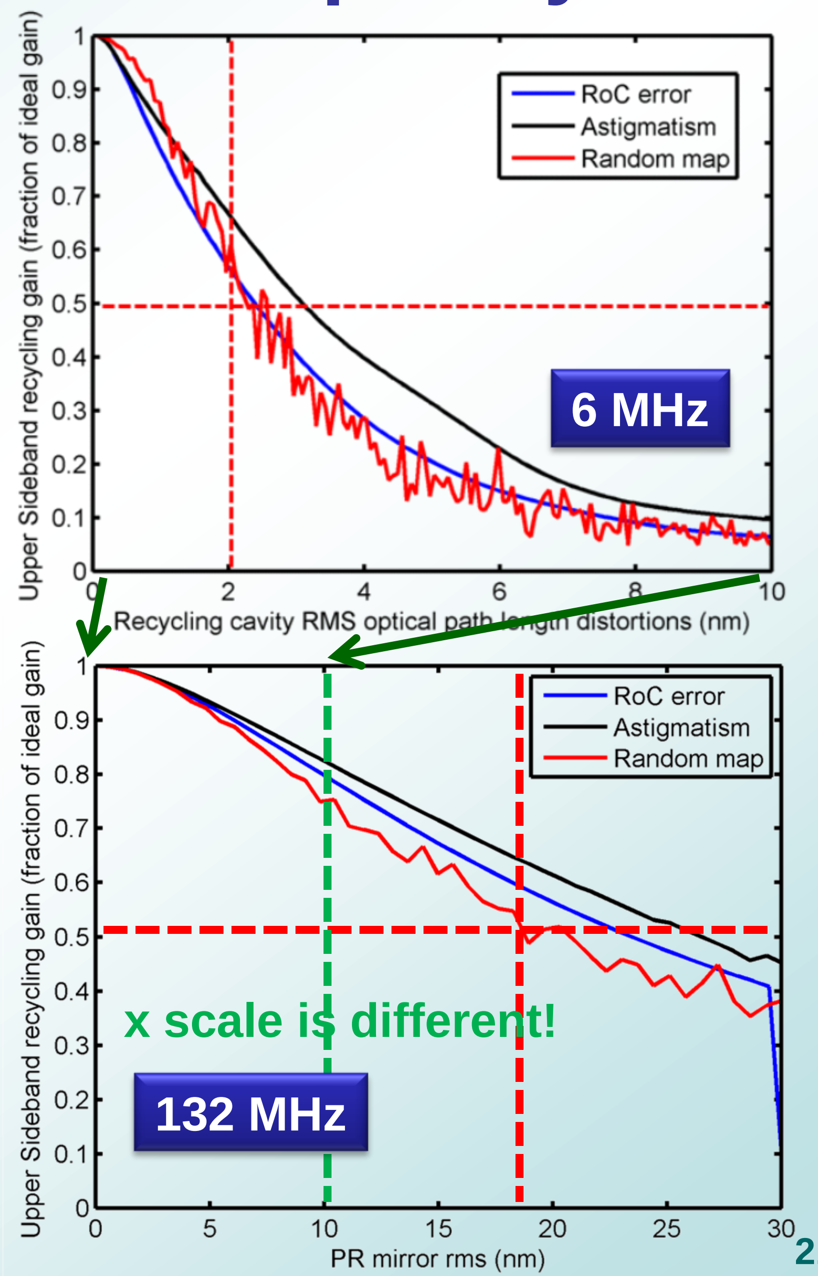
Additional modulation frequency

- Phase cameras are very sensitive, but also have low dynamic range (using main 6 MHz sidebands we get about 3 nm RMS)
- Moreover, we need to control the ITF while performing the measurement
- We foresee an additional modulation at 132 MHz
  - Due to Schnupp asymmetry, they have very low recycling gain inside PRC
  - They are about 10 times less sensitive to PRC optical length distortion
  - They will provide both robust ITF control signals and phase camera images for a coarse compensation

VIR-0377B-11 (July 2011)



Thermal effects

- In addition, when power builds up inside the arms, absorption becomes important
  - Deformation of test mass HR faces (mainly change in RoC)
  - Lensing in the input mirror substrates

	Substrate absorption (ppm/cm)	Coating absorption (ppm)	Absorbed power (mW)
ITM	0.3	1	694
ETM	3	0.5	330
BS	0.3	2	34
PRM	3	2	13
CP	1	1*	26
POP	1	1*	52

Absorptions at 125W input power

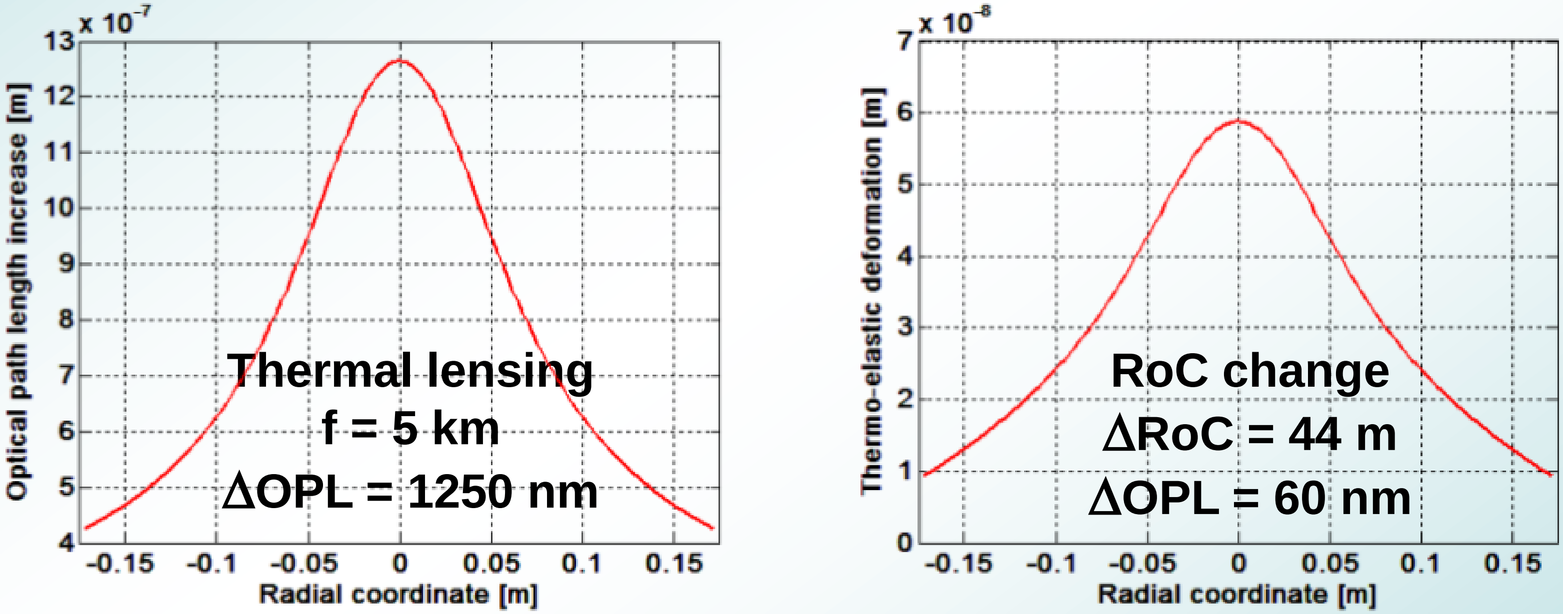
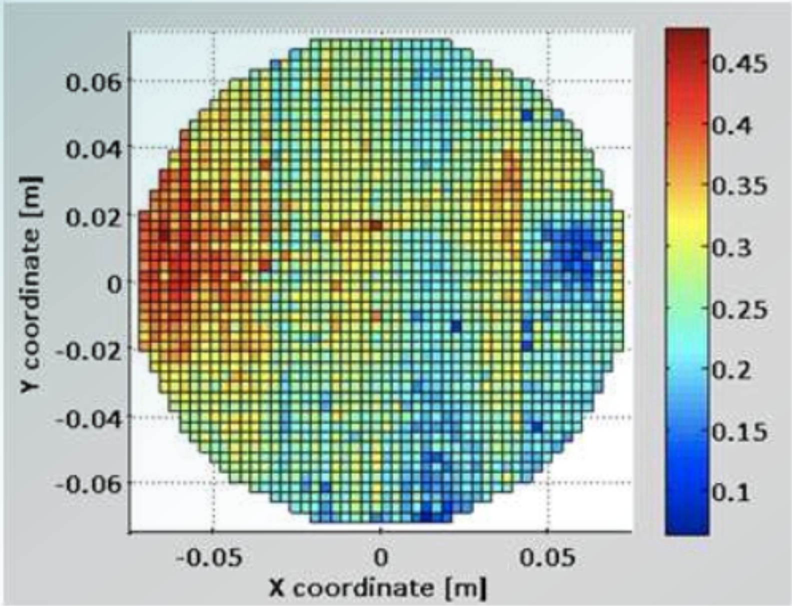
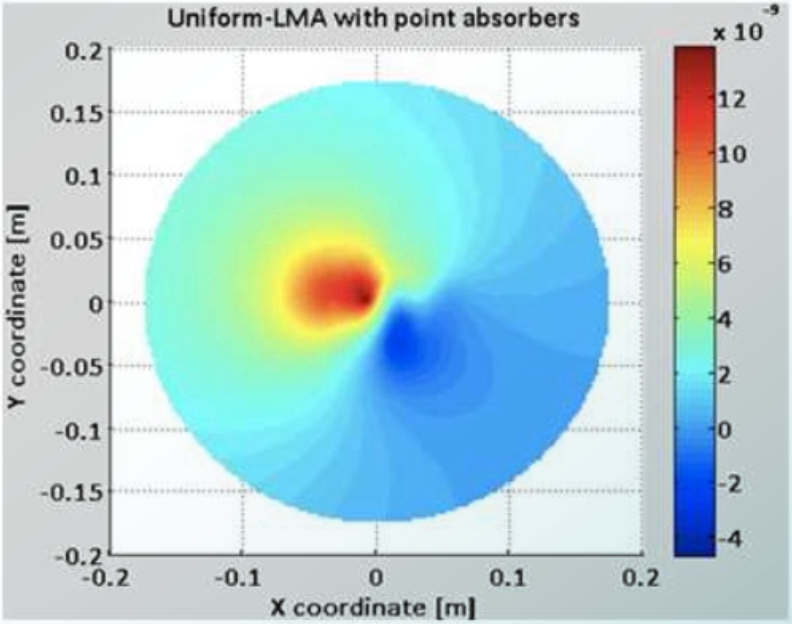


Figure 6.2: Left: optical path length increase in AdV TM due to substrate and coating absorption, corresponding to a focal length of about 5 km. Right: thermoelastic deformation of the HR surface in AdV TM, corresponding to a Gaussian weighted RoC increase of the test masses of about 44 m (about 10 m for unweighted fit).

Non uniform absorptions

- Coating absorption is not uniform
- This introduces non axisymmetric distortions (5.6 nm RMS)





Left: coating absorption map (ppm) on an aLIGO test mass. Right: simulation of the resulting non uniform optical path length distortion for 125 W of input power

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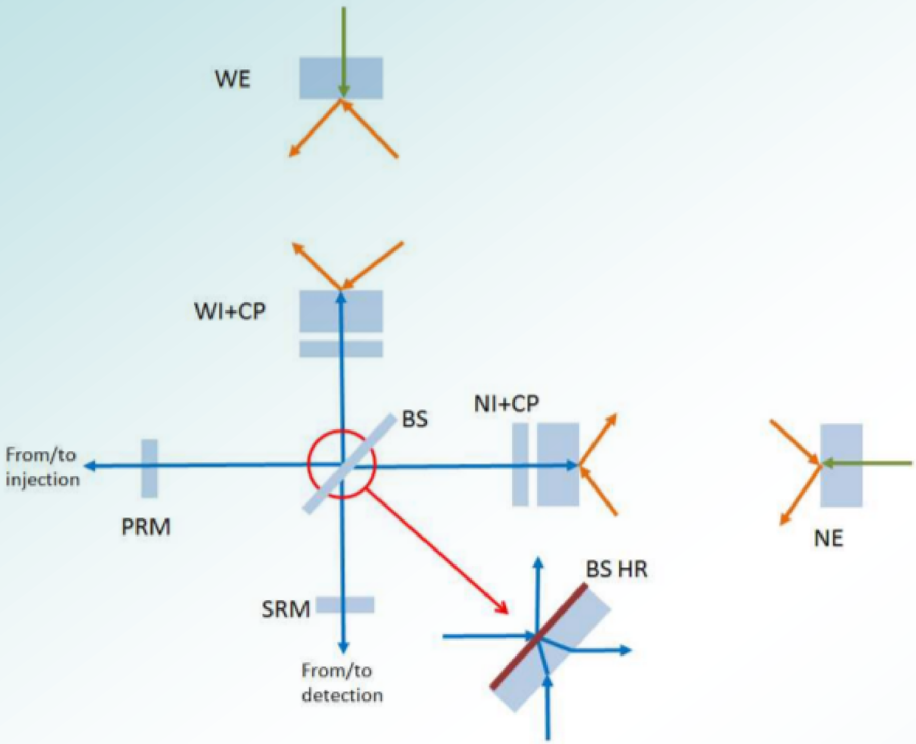
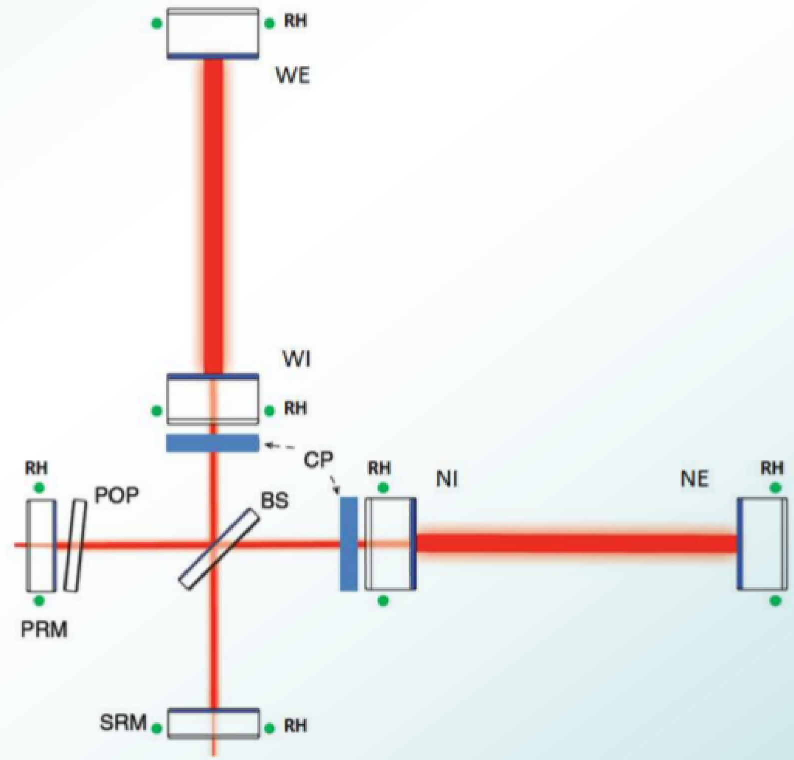
Thermal compensation system



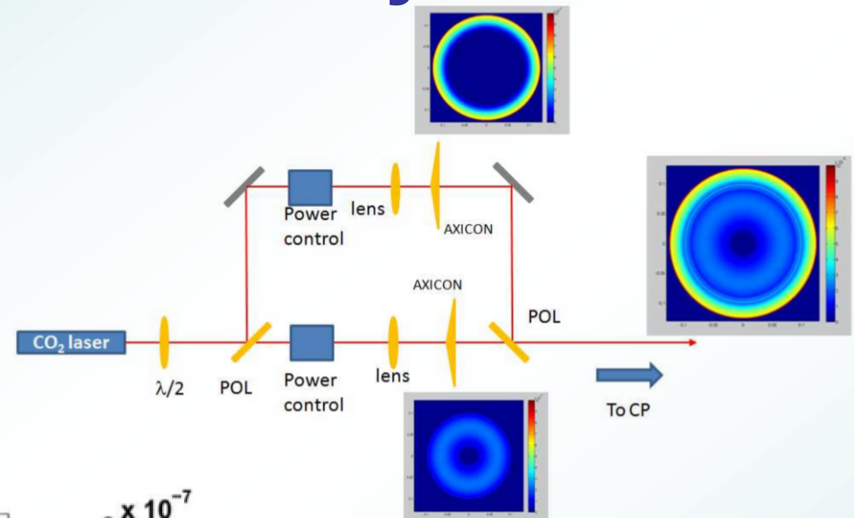


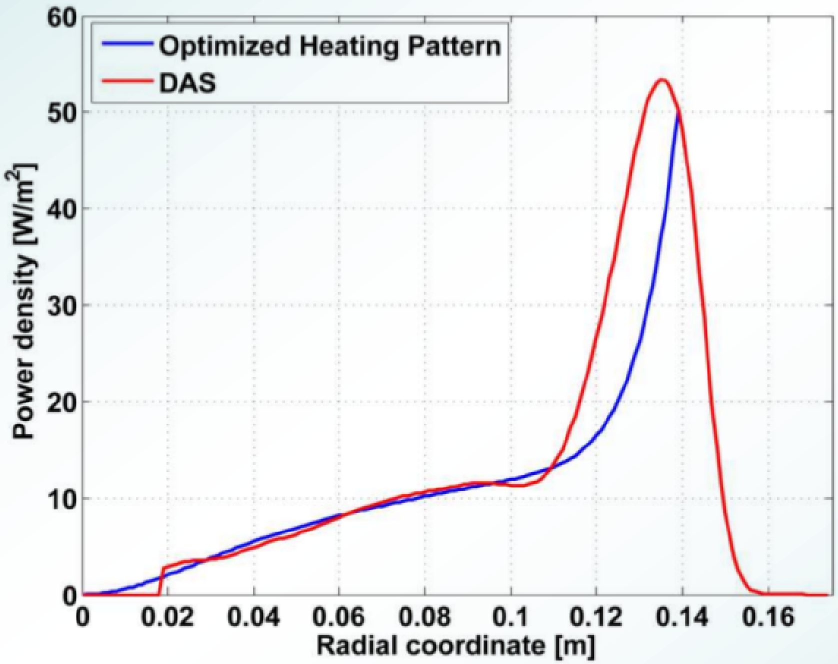
Sensing: Hartmann wave-front sensors and phase cameras

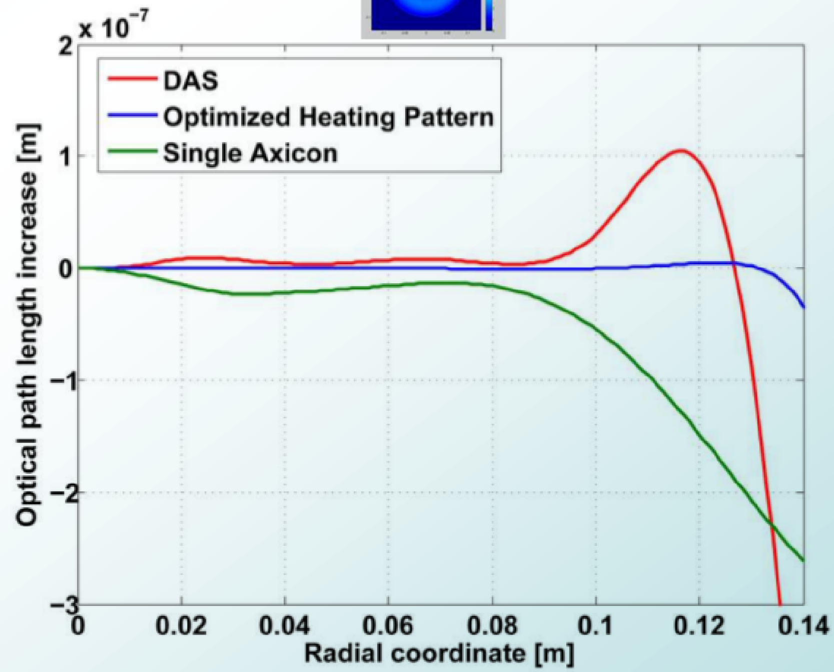
Actuation: ring heaters, CO_2 projectors (double axicon and scanning system)

Thermal compensation system

- **Double axicon system (DAS)** to compensate the axisymmetrical distortions
  - Heating pattern is very close to the ideal one to compensate Gaussian heating







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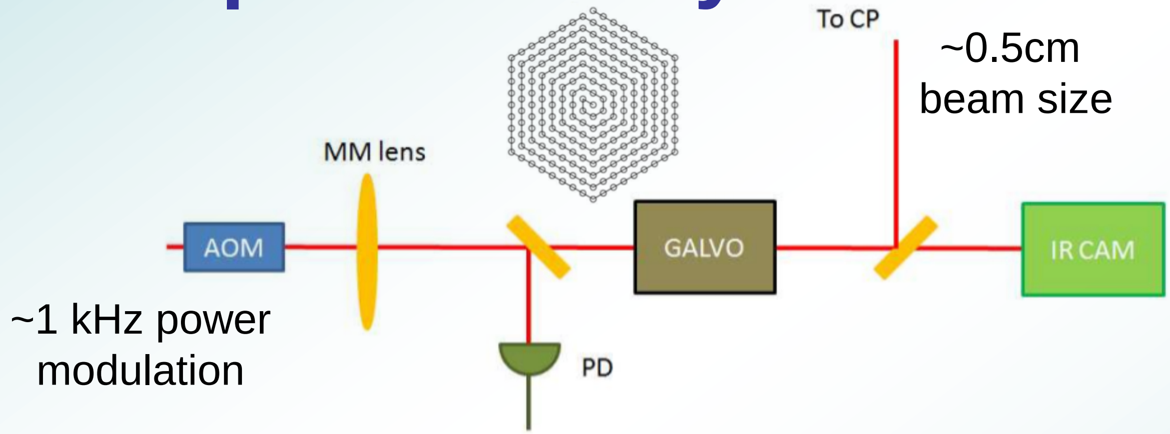
V. Fafone et al, paper in preparation

Thermal compensation system

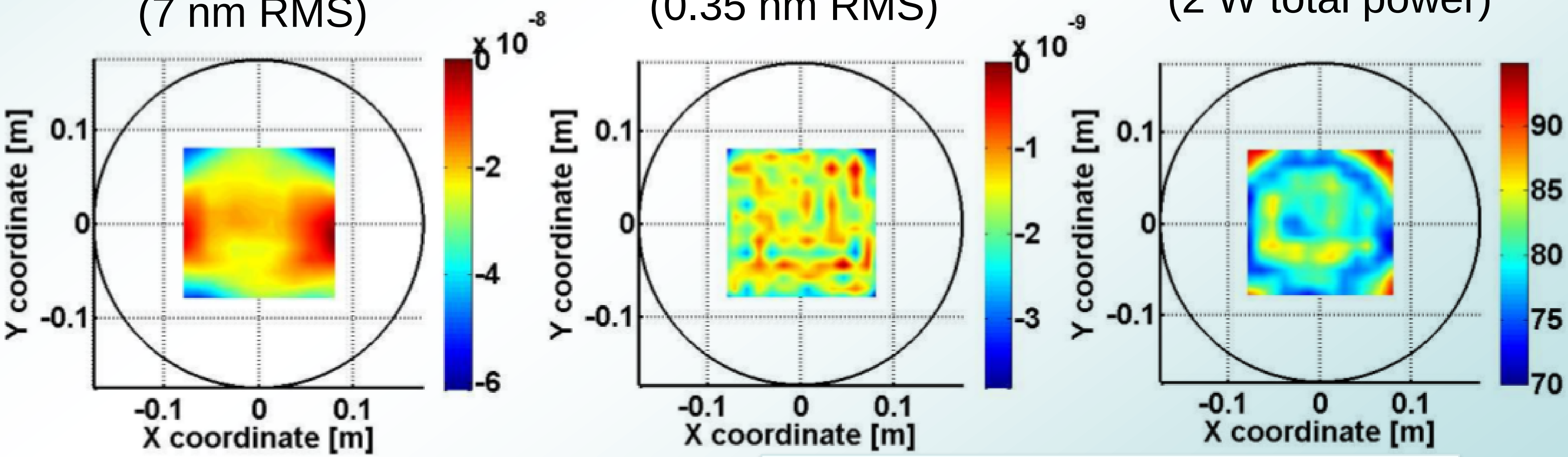
- Double axicon will compensate the symmetric part
- Residual non axisymmetric defects will be compensated using a scanning system
  - Only few watts will be needed



Residual DAS only (7 nm RMS)

Residual DAS + scanning (0.35 nm RMS)

Scanning pattern (2 W total power)



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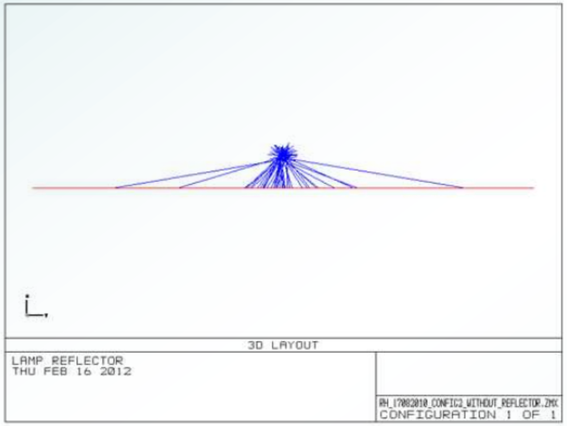
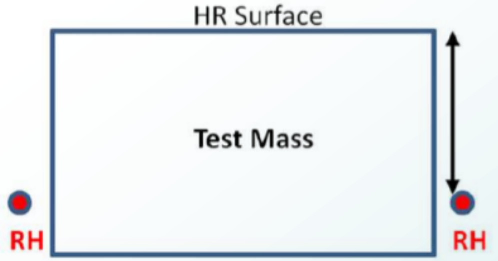
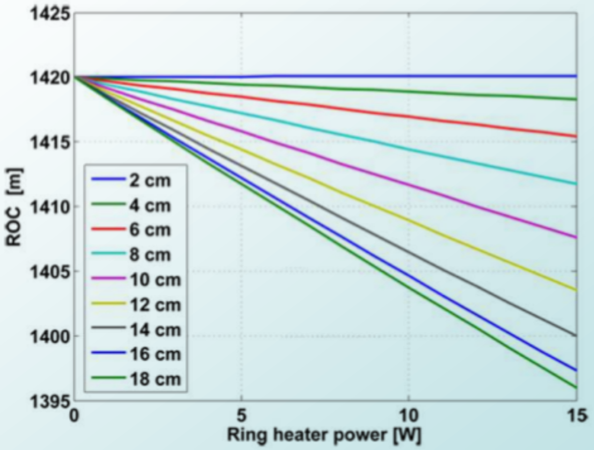
V. Fafone et al, paper in preparation

Radius of curvature compensations

- Baseline is to use ring heater on all test masses, PR and SR mirrors
  - They will be needed also to correct for the “cold” RoC errors (polishing specifications ±10m, requirement ±2m)
- CHRoCCs (see last year’s presentation) are not considered as baseline
  - Will create larger thermal lensing in input mirrors
  - Are not easily adapted to PR, due to pick-off plate
- Zemax simulation to compute heating pattern on mirrors (use shielded elements)
- Finite element analysis to compute RoC change (optimize position)







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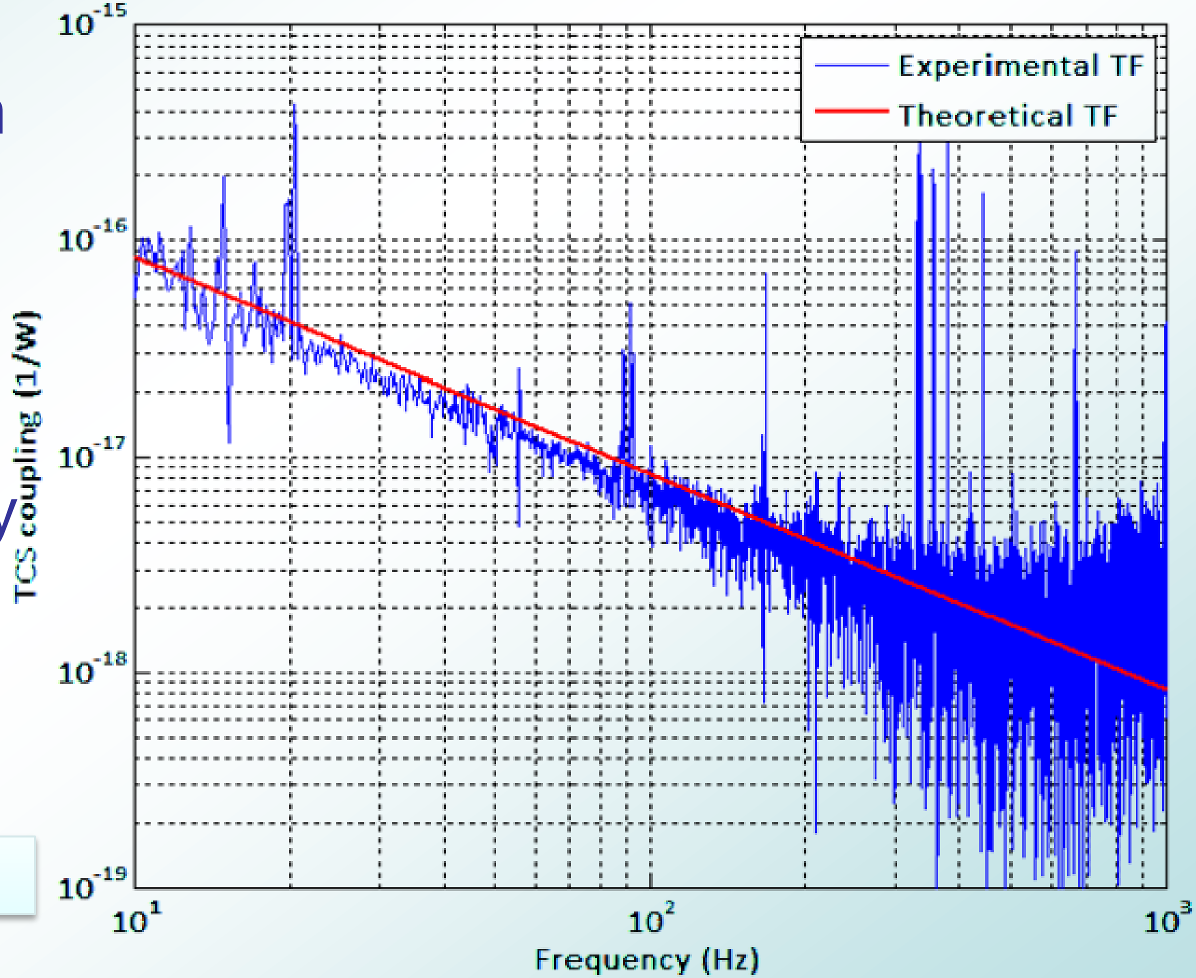
V. Fafone et al, paper in preparation

TCS noise couplings

- Couples mainly through thermo-elastic and thermo-refractive effects
- Use of compensation plates largely reduces the impact of CO_2 noise
- Couplings can be computed analytically (good agreement with measurements performed in Virgo+)



VIR-0512B-09 (Sept. 2009)

TCS noise couplings

- Using CO_2 RIN measured in Virgo+ (stabilized with one photodiode

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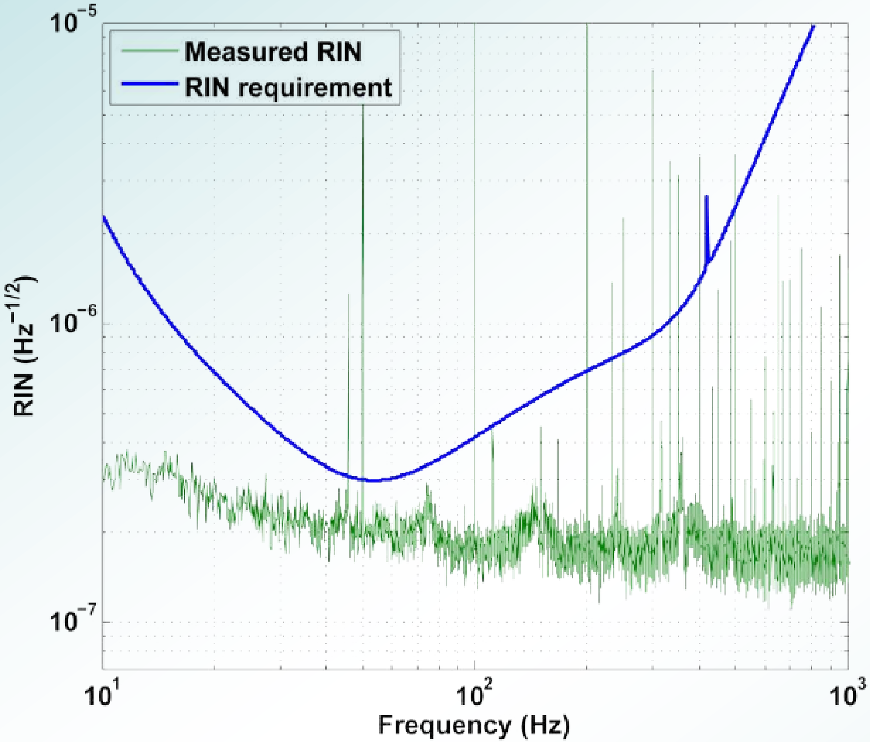
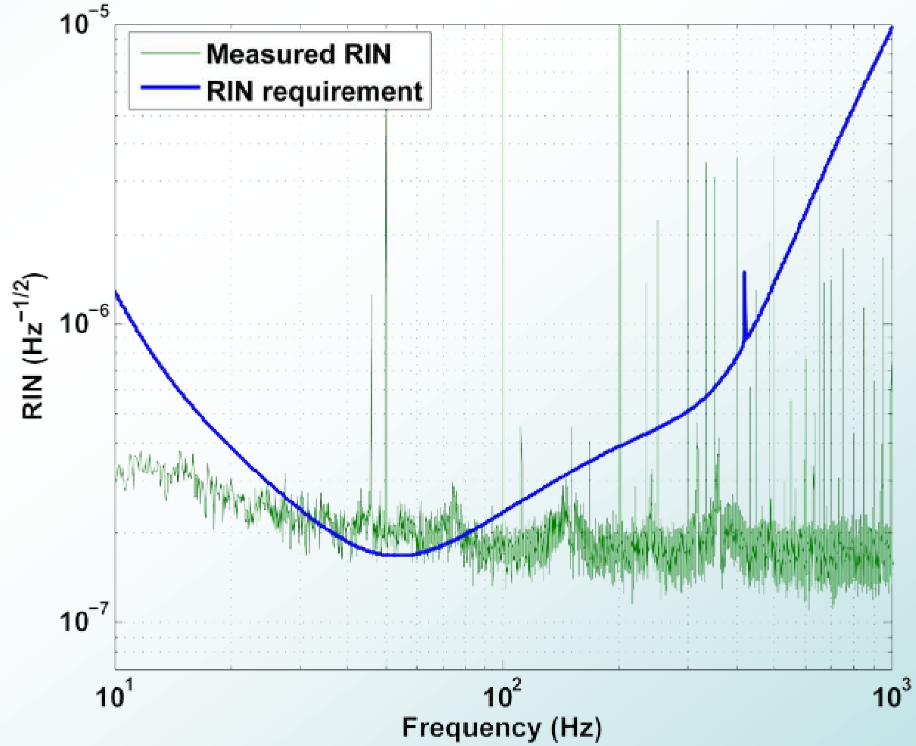


Coupling of double axicon noise



Coupling of scanning system noise (a factor sqrt(2) missing, will be gained using 2 diodes instead of 1)

CONCLUSIONS

Summary

- High power laser sources
  - Two different strategies: AdV will use one-stage amplifier based on rod-type fibers. Two 100W lasers will be combined to deliver 200W
- Optical length distortions are crucial (thermal effects, surface figure errors, transmission inhomogeneities, etc.)
  - Stable cavities are more robust from the optical point of view, but more complex from mechanical and control ones **(aLIGO path)**
  - Marginally stable cavities are optically more touchy, but simpler from mechanical and control point of view **(AdV path)**
- In all cases detailed simulations are needed to proper design the optical and compensation system

Advanced Virgo strategy

- MSRC forces us to meet more stringent requirements on optical path distortions
- It is not possible to get them out of the box
- We need to implement adaptive optics strategies
- Sensing
  - Phase cameras to measure “cold” defects
  - Hartmann wave-front sensors to track thermal effects
- Actuation (thermal compensation system)
  - Axisymmetric CO_2 projector on CP (PRM + ITM)
  - Non-symmetric CO_2 (scanning system) on CP (PRM+ITM)
  - Ring heaters (PRM + ITM + ETM)
- Risk reduction strategy with additional modulation frequency
  - We’ll be able to control the ITF even in presence of large OPL errors


Thank you for your attention