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Integrated dynamical thermal compensation techniques for Advanced Virgo

GRASS, Padova, October 17th -18th 2019

Outline

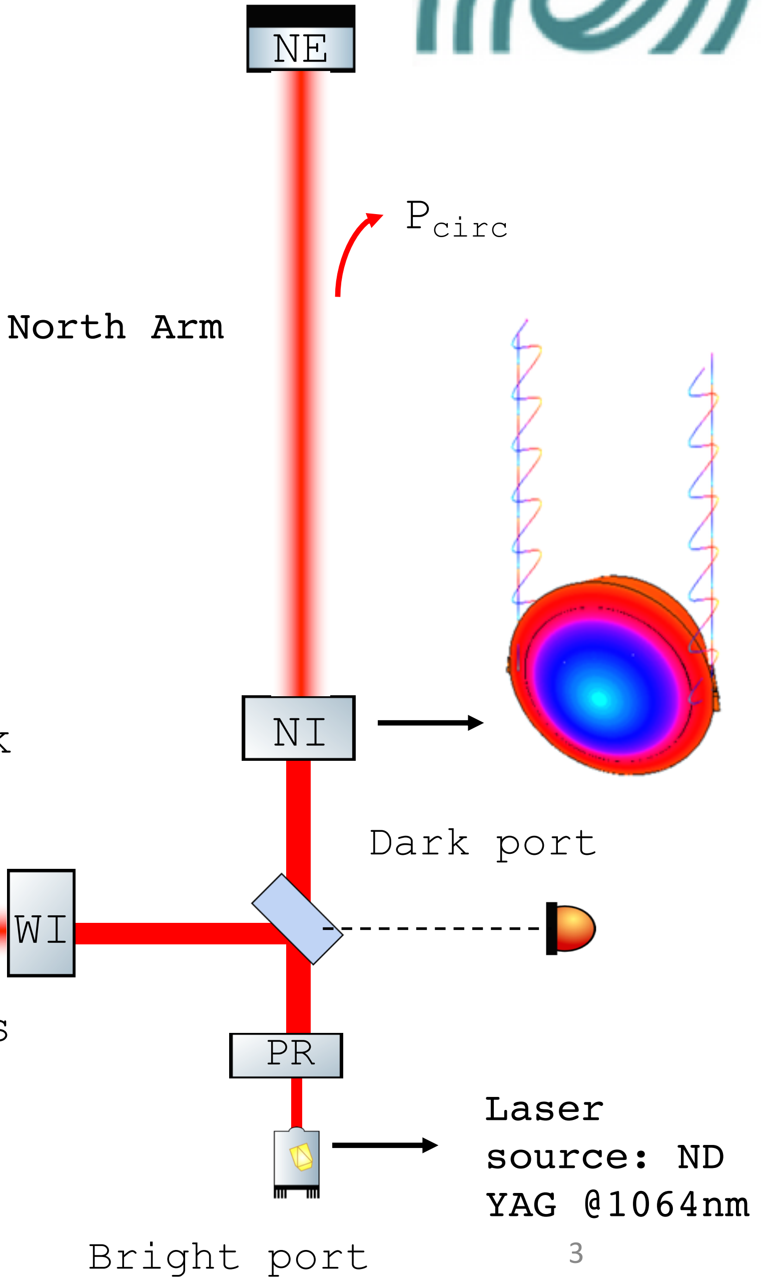
- Ground Based gravitational wave interferometers
  - General features
- Thermal effects in the mirrors
  - Fabry-Pérot core optics
- Thermal compensation system
  - Sensors
  - Actuators
- Thermal compensation system payoff
- What we learned during O3
- TCS integrated strategies:
  - CO_2 laser central heating to mimic the YAG
  - Ring heater fast response
  - CO_2 laser central heating to compensate RH thermal lensing
- Conclusions

Ground Based gravitational wave interferometers

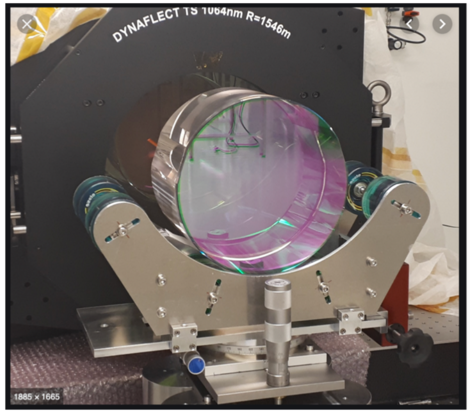
- Best gravitational-wave hunter in the range 10Hz-10kHz
- Michelson interferometer (ITF) with Fabry-Pérot optical cavities:
  - $\Delta\phi = \frac{4\pi}{\lambda} h L_{eff}$ L_{eff}=850 km
  - G_{FP}=287 (for Advanced Virgo)

the ratio between the circulating and incident powers in the FP-cavity.

- Suspended cavity mirrors
- Power recycling cavity to recycle the power reflected back towards the symmetric port:
  - G_{PRC}=43
- Pound-Drever Hall technique to control the ITF, conditions of resonances in the cavities:
  - ➔ carrier resonant in all cavities
  - ➔ sideband resonant in the power recycling cavity (used to control the ITF)



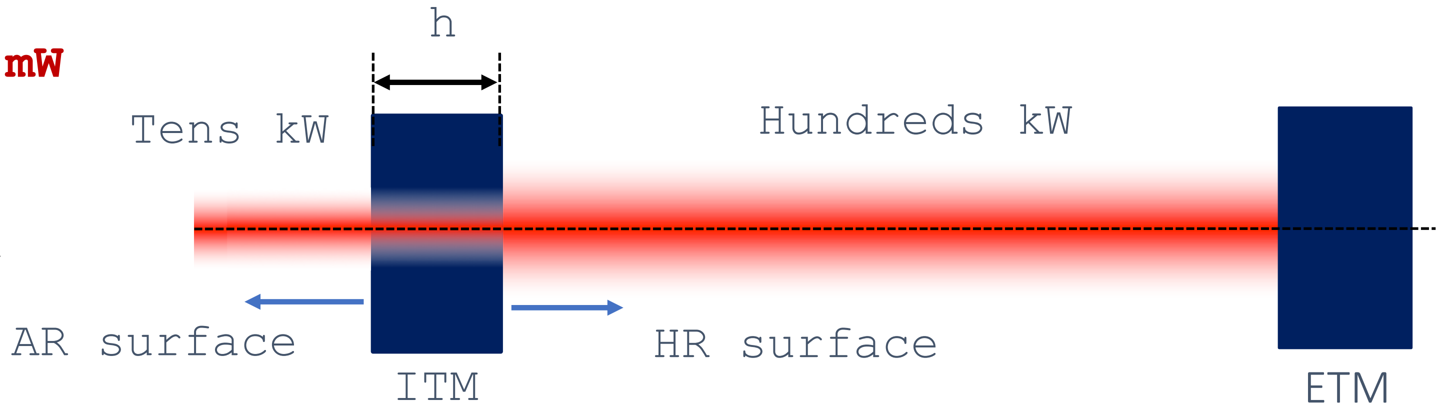
Thermal effects in the mirrors



- **When the ITF is ready to acquire science data:**
  ➔ $P_{circ}=P_{inp}/2 \times G_{FP} \times G_{PRC}$ ~**123 kW** (for P_{inp}= 20W)

- The power absorption inside the ITM coating is of about **0.5 ppm**

  ➔ P_{abs} = 0.5 ppm x 123 kW ~ **60 mW**

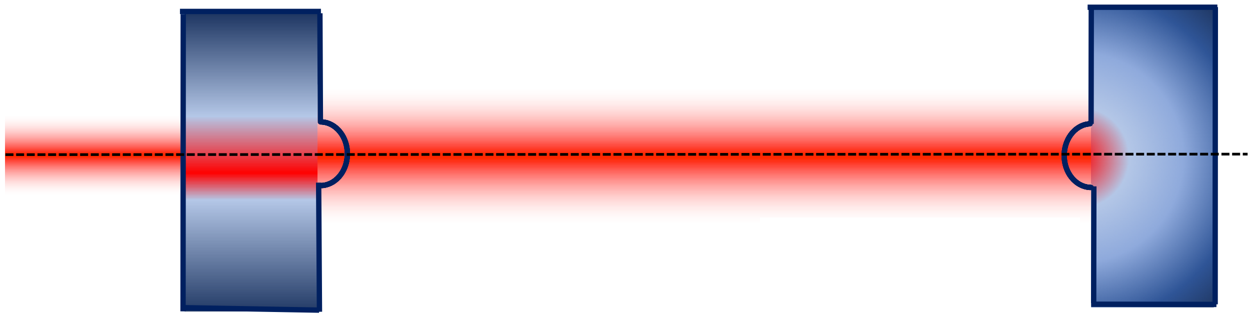


- Thermal lensing inside the ITM

$$\Delta OPL_T \approx \frac{dn}{dT}\int_0^h \Delta T\, dz$$

- Thermoelastic deformation on ITM and ETM

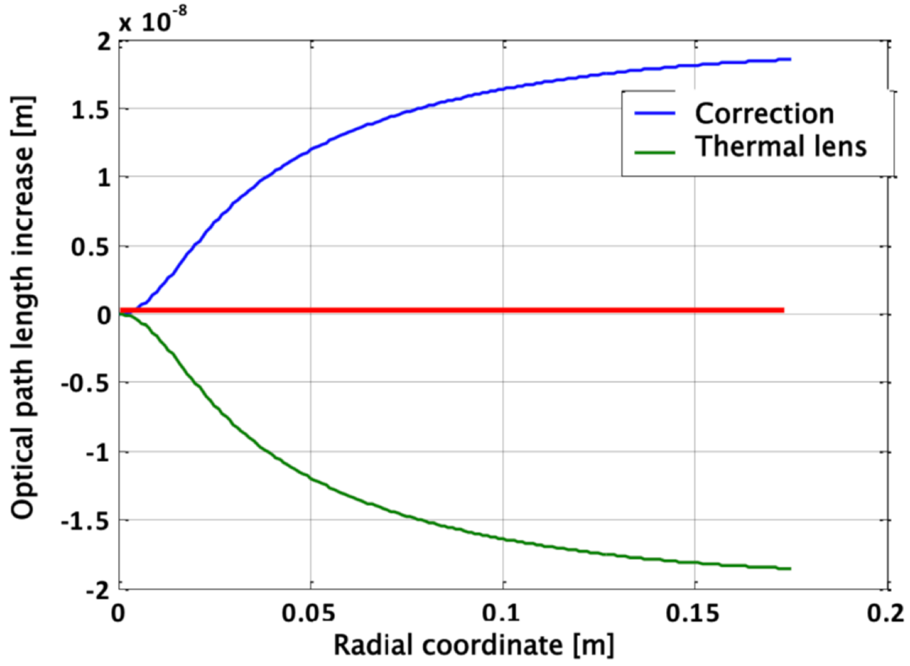
$$\Delta OPL_R \approx 2\alpha \int_0^h \Delta T\, dz$$



➔ **Thermal Compensation System (TCS) has to compensate thermal lensing and thermo-elastic deformation.**

Thermal compensation system guidelines

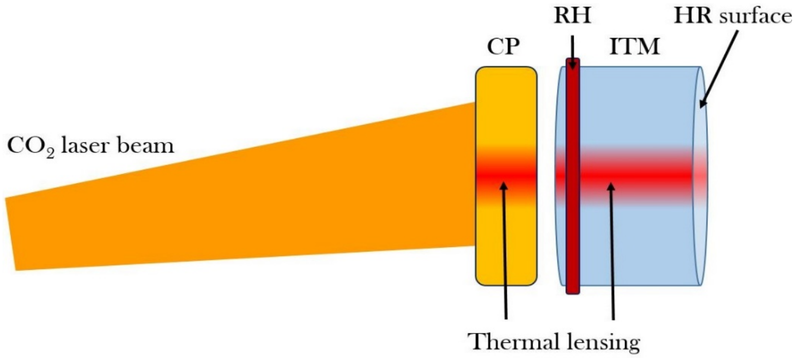
- Mirrors are suspended so they cannot be touched;
- the only “touchless” way to heat the mirror is by shining it with a radiation;
- Wavefront aberration must be compensated with a precision better than 2nm RMS;
- Radius of curvature of mirrors must be controlled within +/- 2m

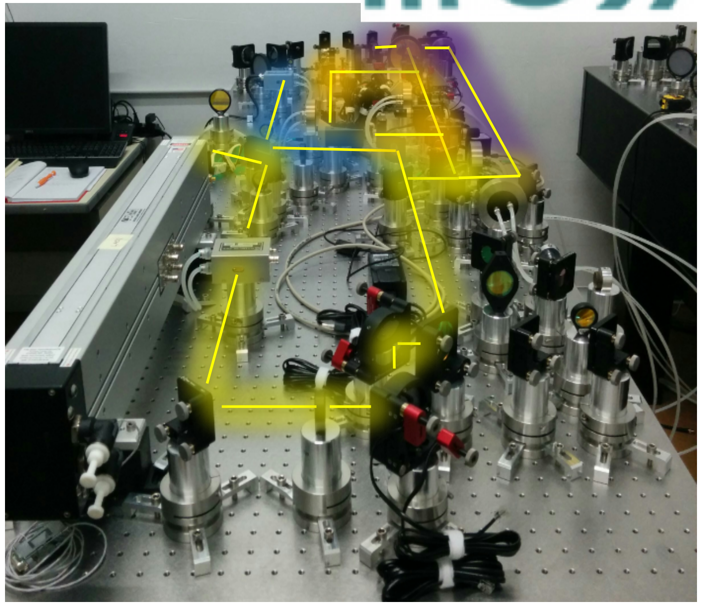


- Induce in the optics an aberration equal but opposite to the thermal effect.

Thermal compensation system: CO_2 actuators

- **To compensate thermal lensing**

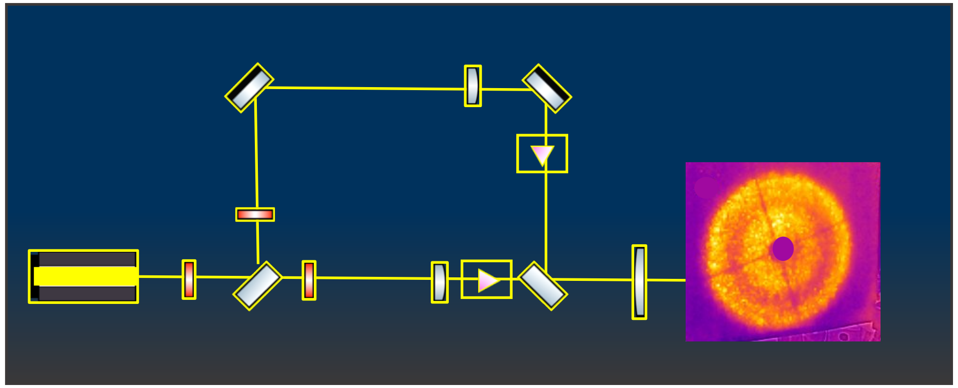




- High-power CO_2 lasers projector impinging on a compensation plate to correct thermal lensing
- CO_2 wavelength (λ=10.6 μm) completely absorbed by silica.

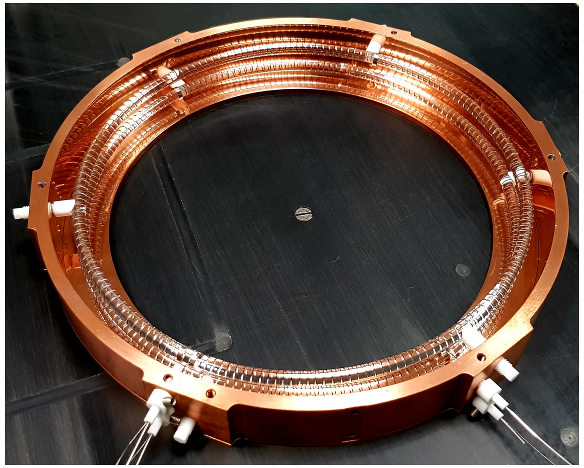
Three different actuation lines:

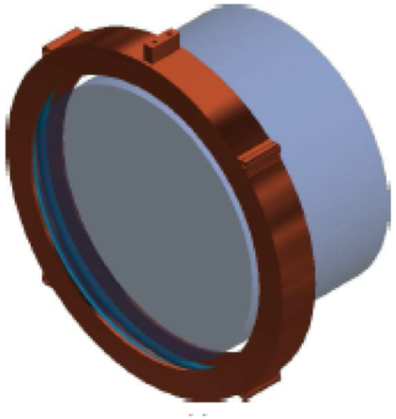
- axi-symmetric centred pattern (Central heating, CH);
- axi-symmetric annular correction (Double Axicon System, DAS);
- not axi-symmetric residual patterns (galvo scanning system, SS).



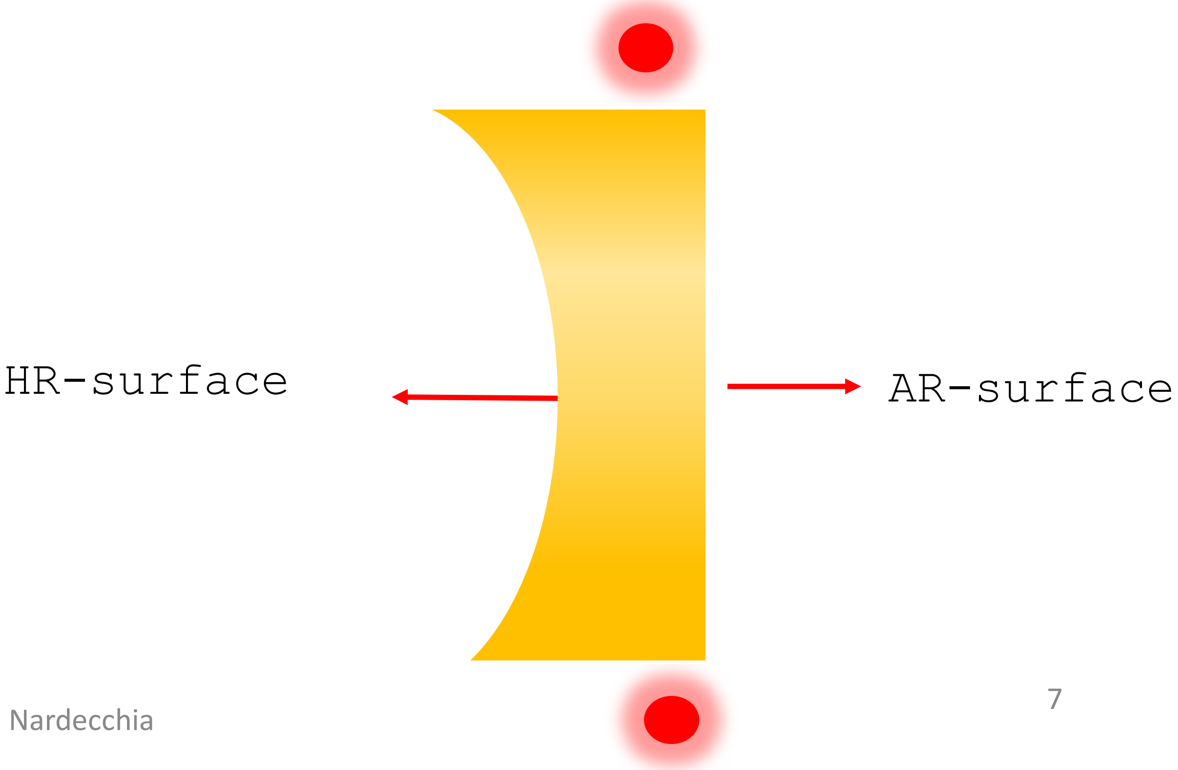
Thermal compensation system: Ring heaters actuators

- **To compensate thermoelastic deformation**





- Radiative element to heat the periphery of the optics:
  - 2 Pyrex Glass ring
  - NiCr conductive wire
  - Copper shield
- R= 50 Ω and i= 1 A
  ➔ P_{RH}= 100 W (maximum)
- Linear dynamic:
  $RoC_{ITM}=-0.95*P_{applied}+1426$ m
  $RoC_{ETM}=-1.28*P_{applied}+1696$ m



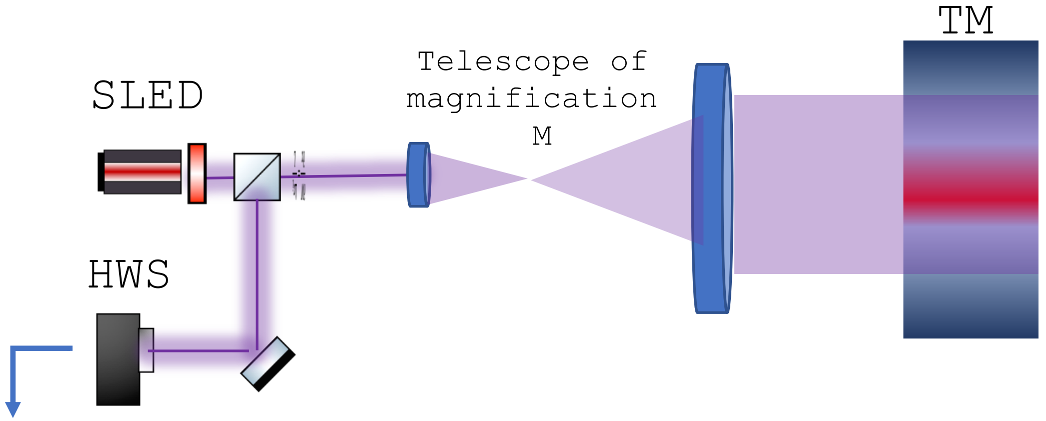
Advantage
- HR surface change almost completely spherical

Downside
- Long thermal constant (~10 hr)

Thermal compensation system: Hartmann Wavefront sensors

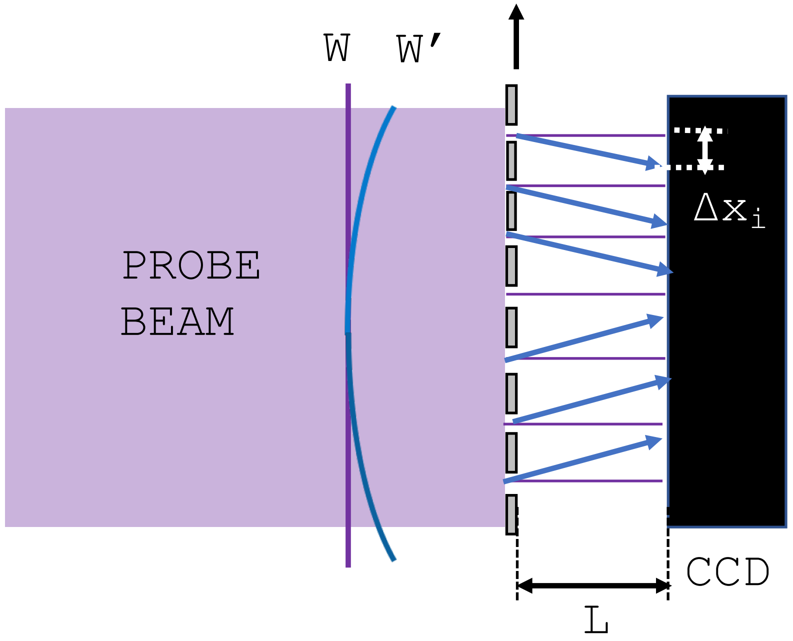
- **Requirement:** noise <2nm
- It measures the change of a 'live' wavefront relative to a reference wavefront through an uncoherent probe beam [fiber coupled superluminiscent diode (SLED)];

Conceptual scheme

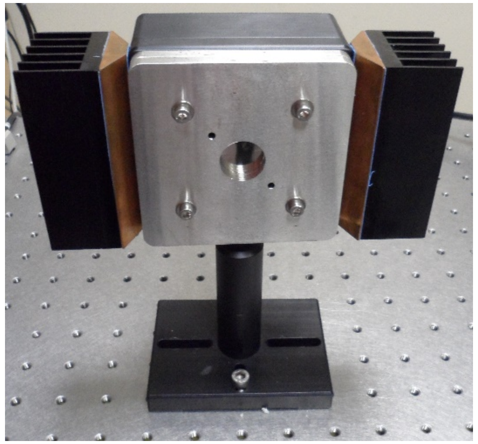


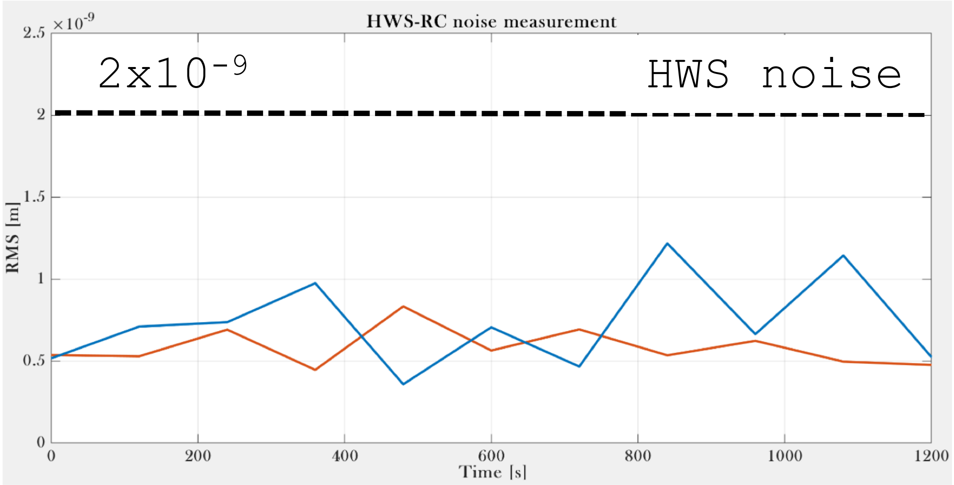
In the image plane of the aberrated surface ➔ $RoC_{TM} = M^2 RoC_{HWS}$

HWS plate



$$\frac{\partial W}{\partial x} = \frac{\Delta x_i}{L}$$



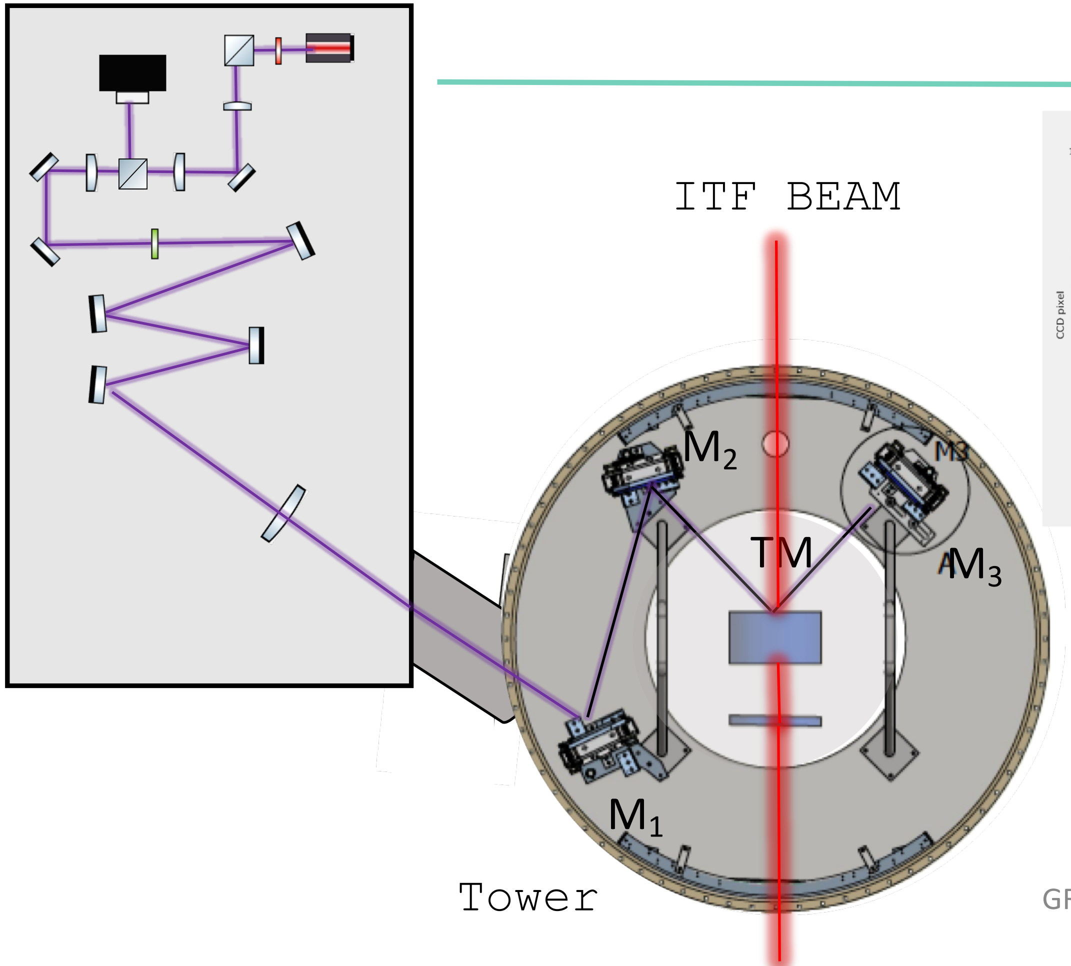


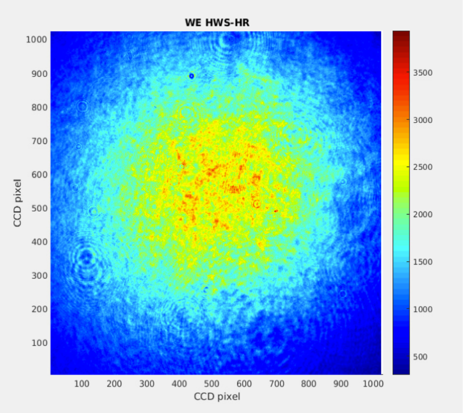
A. Brooks et al, Ultra-sensitive wavefront measurement using a Hartmann sensor, Optical Society of America (010.7350), (2007)

HWS-High reflectivity set up

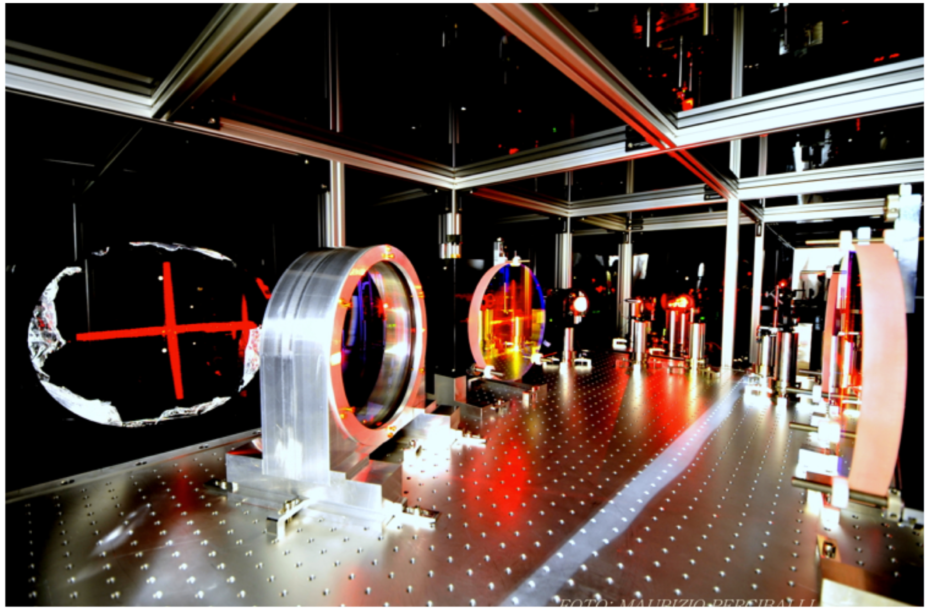
To measure the thermoelastic deformation:

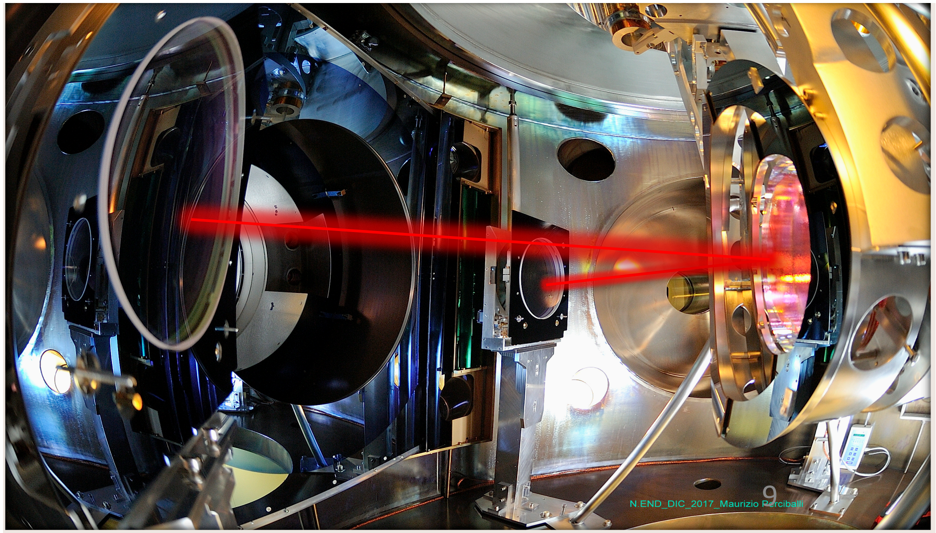
- SLED @880 nm;
- AOI=45° and w^{SLED}_{TM}= 60 mm;
- w^{SLED}_{TM}= 60 mm;
- Double pass;





Credit: M. Perciballi



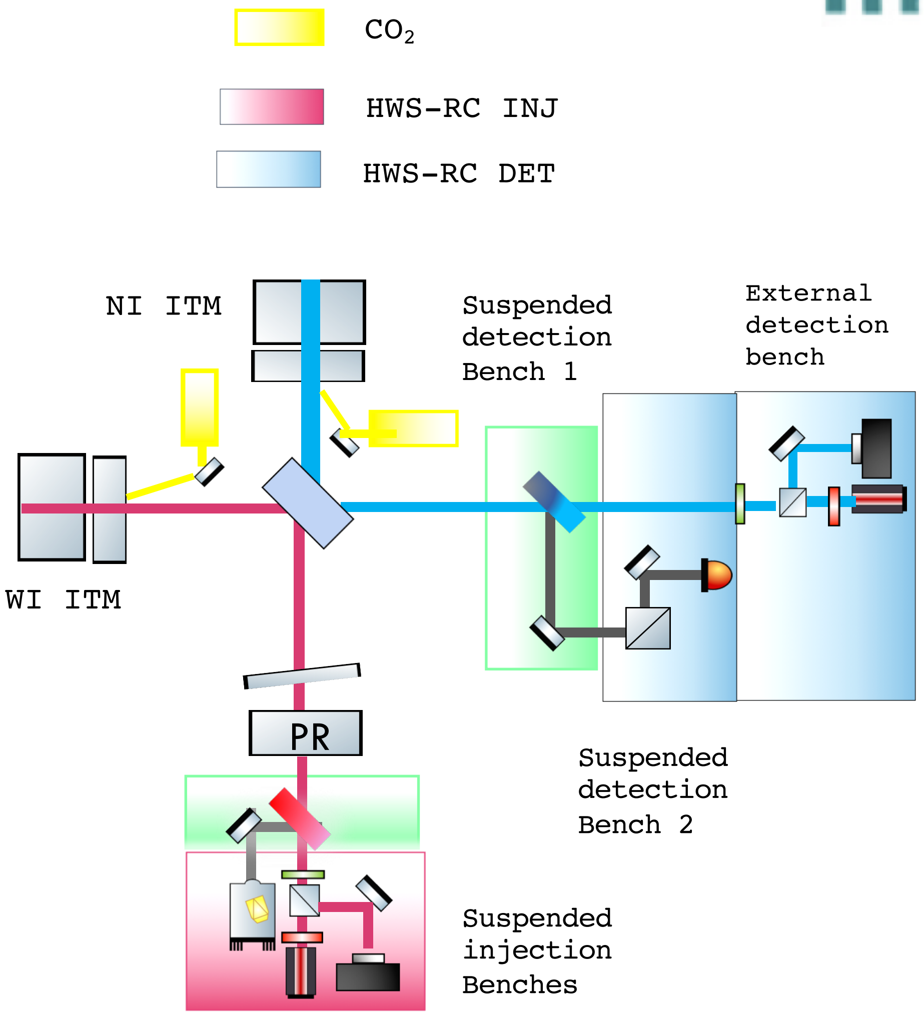


HWS-Recycling cavity (HWS-RC) set up

To measure the thermal lensing in the ITM:

- SLED @750 nm;
- AOI=0°
- w^{SLED}_{TM}= 100 mm;
- Double pass;

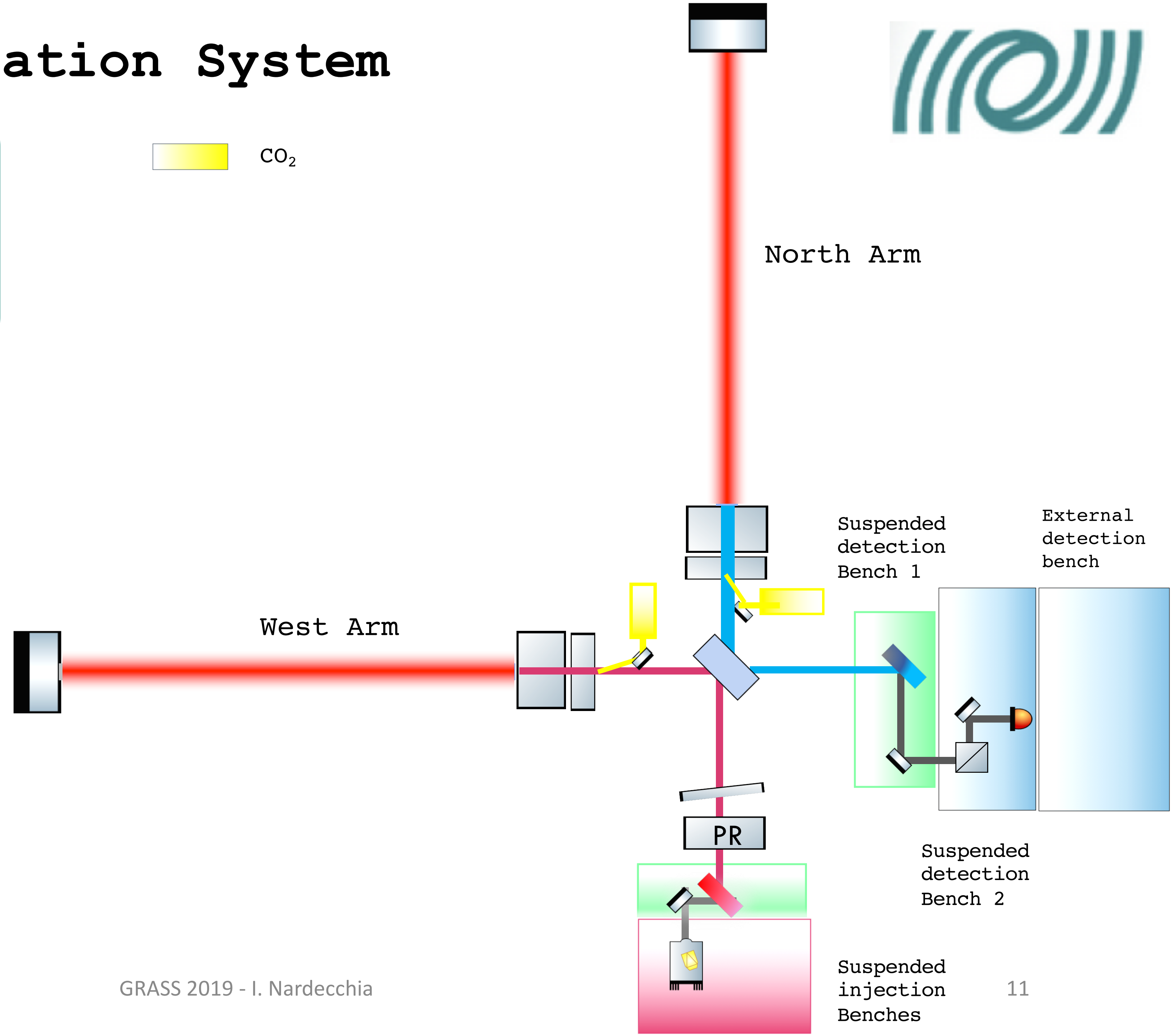
HWS-INJ interrogates WI TM
HWS-DET interrogates NI TM



AdV Thermal Compensation System

TCS actuators :

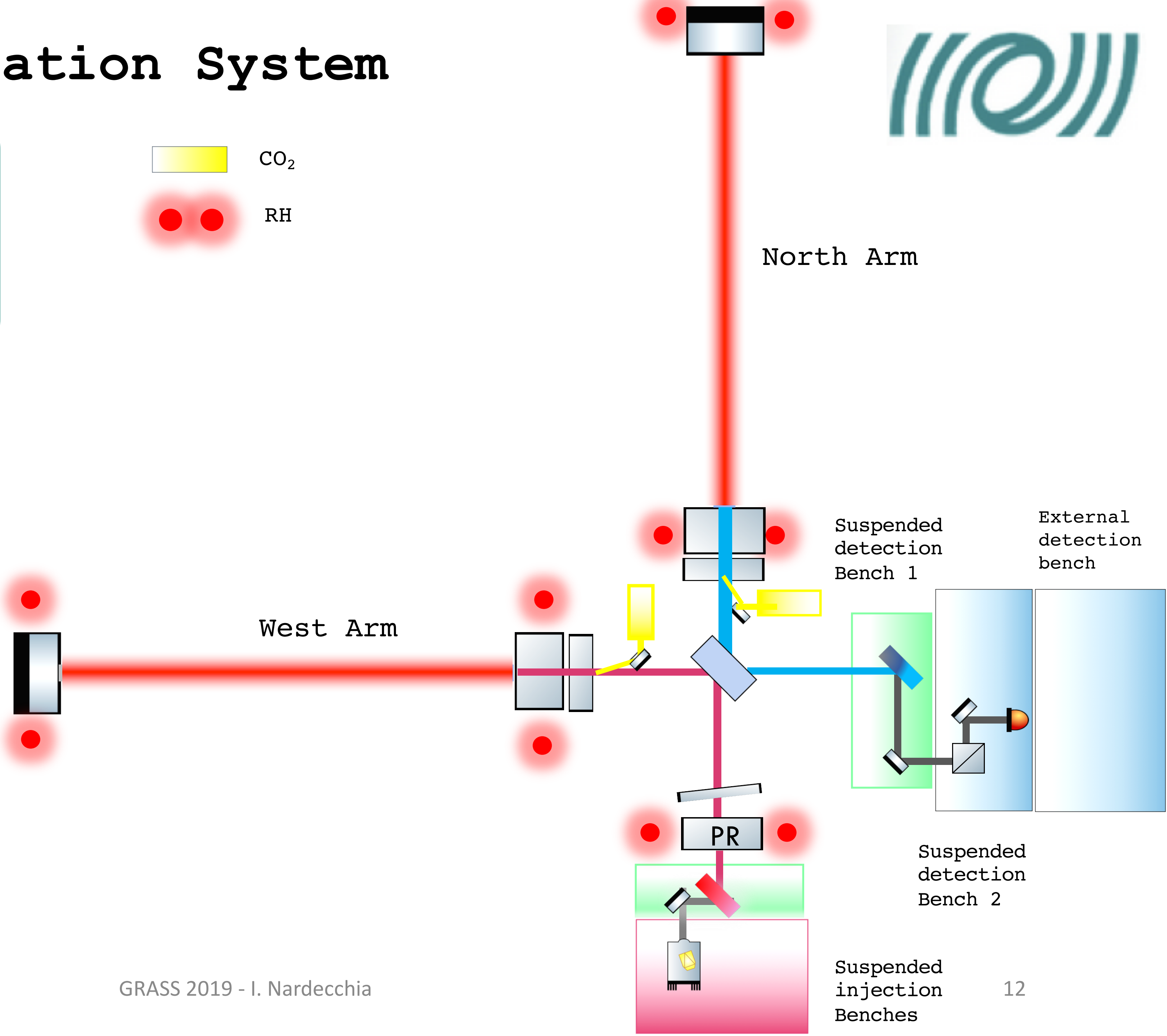
- **CO_2 laser** projector corrects thermal lensing;



AdV Thermal Compensation System

TCS actuators :

- **CO_2 laser** projector corrects thermal lensing;
- Ring Heater (**RH**) acts on the thermoelastic deformation of the HR surface.



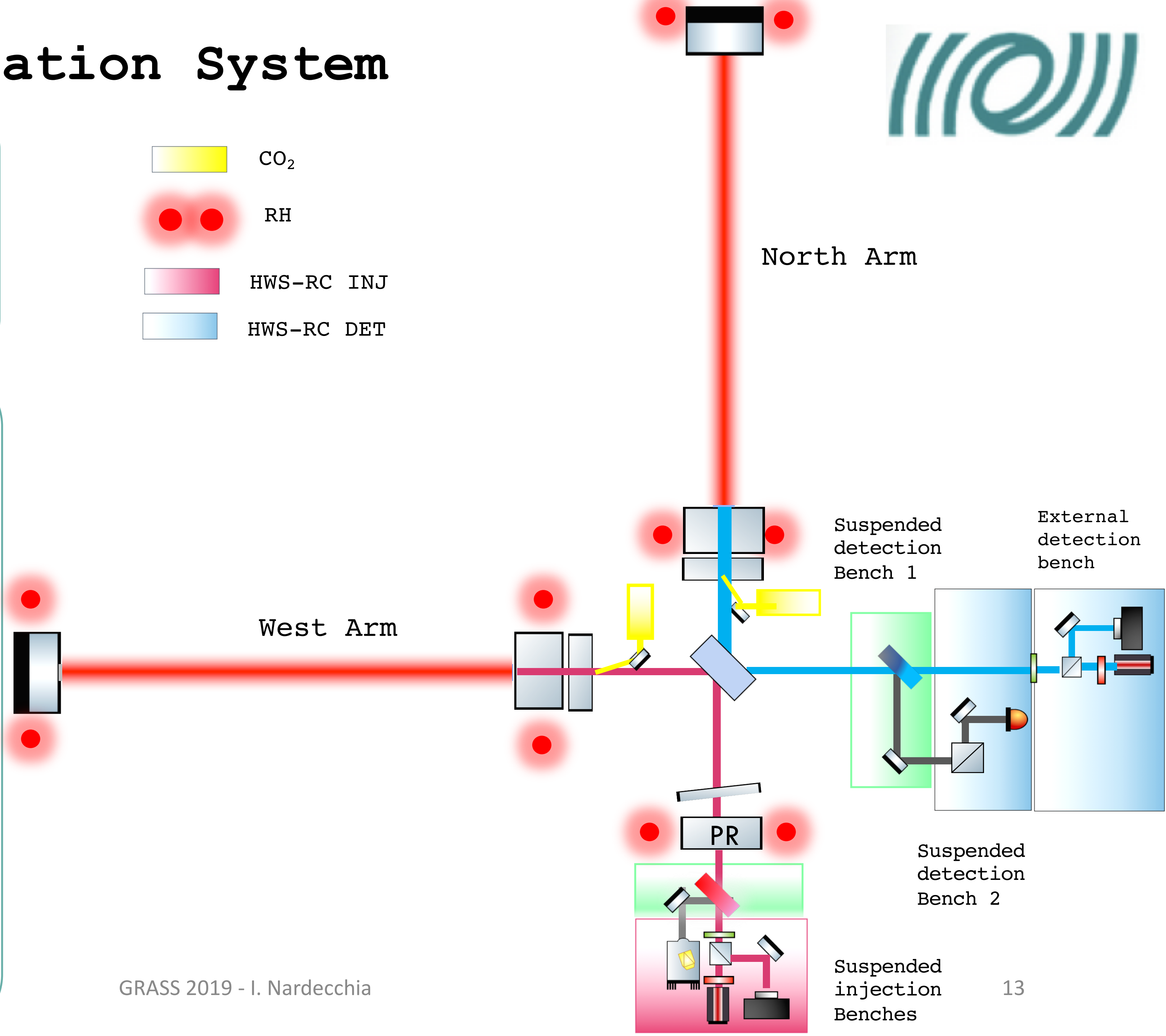
AdV Thermal Compensation System

TCS actuators :

- **CO_2 laser** projector corrects thermal lensing;
- Ring Heater (**RH**) acts on the thermoelastic deformation of the HR surface.

TCS sensors :

- Hartmann Wavefront Sensor in the recycling cavity **(HWS-RC)**: to measure the thermal lensing;



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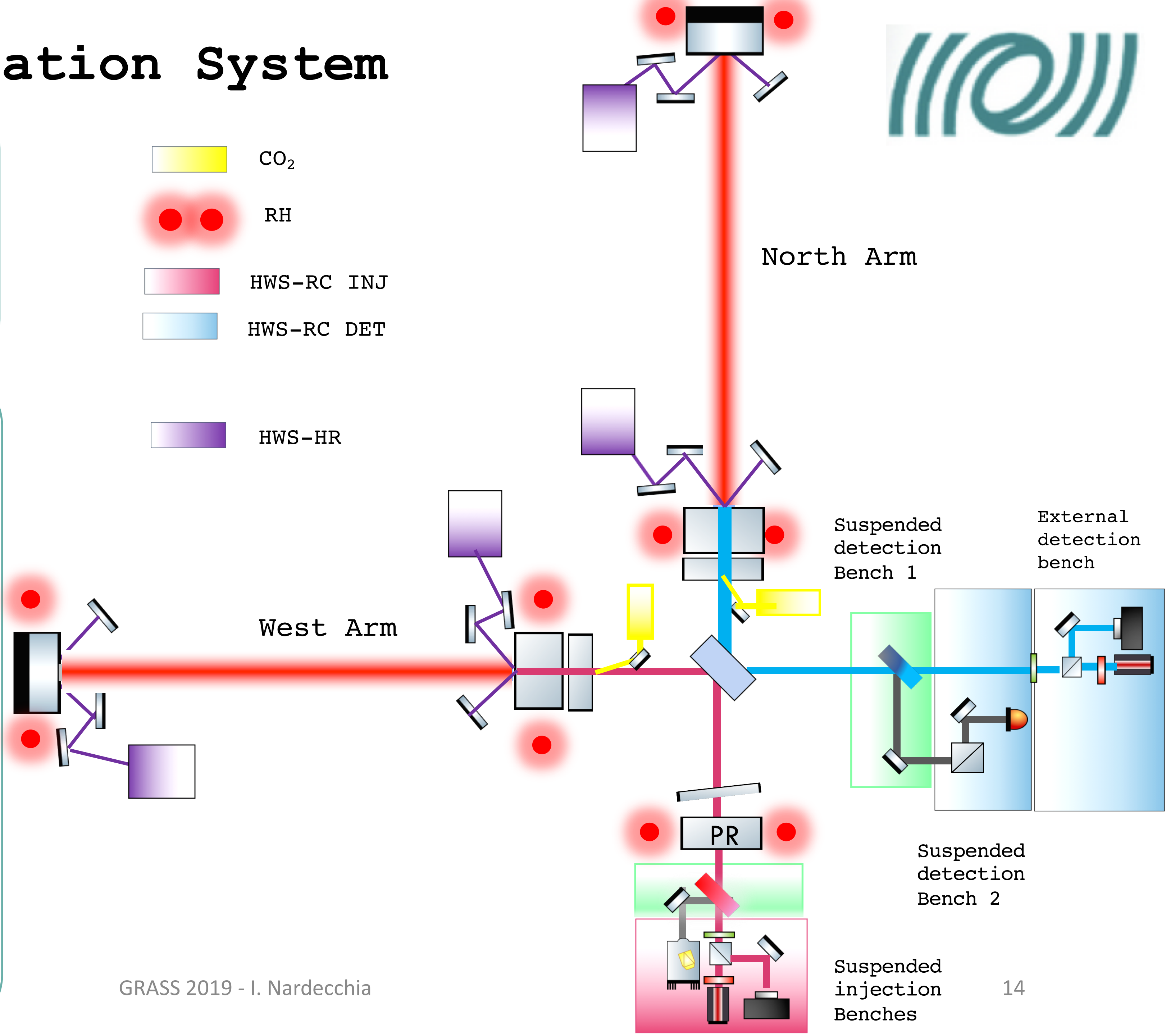
- Hartmann Wavefront Sensor in the recycling cavity **(HWS-RC)**: to measure the thermal lensing;
- Hartmann Wavefront Sensor on the HR surface **(HWS-HR)**: to measure the thermoelastic deformation of the HR surface;



AdV Thermal Compensation System

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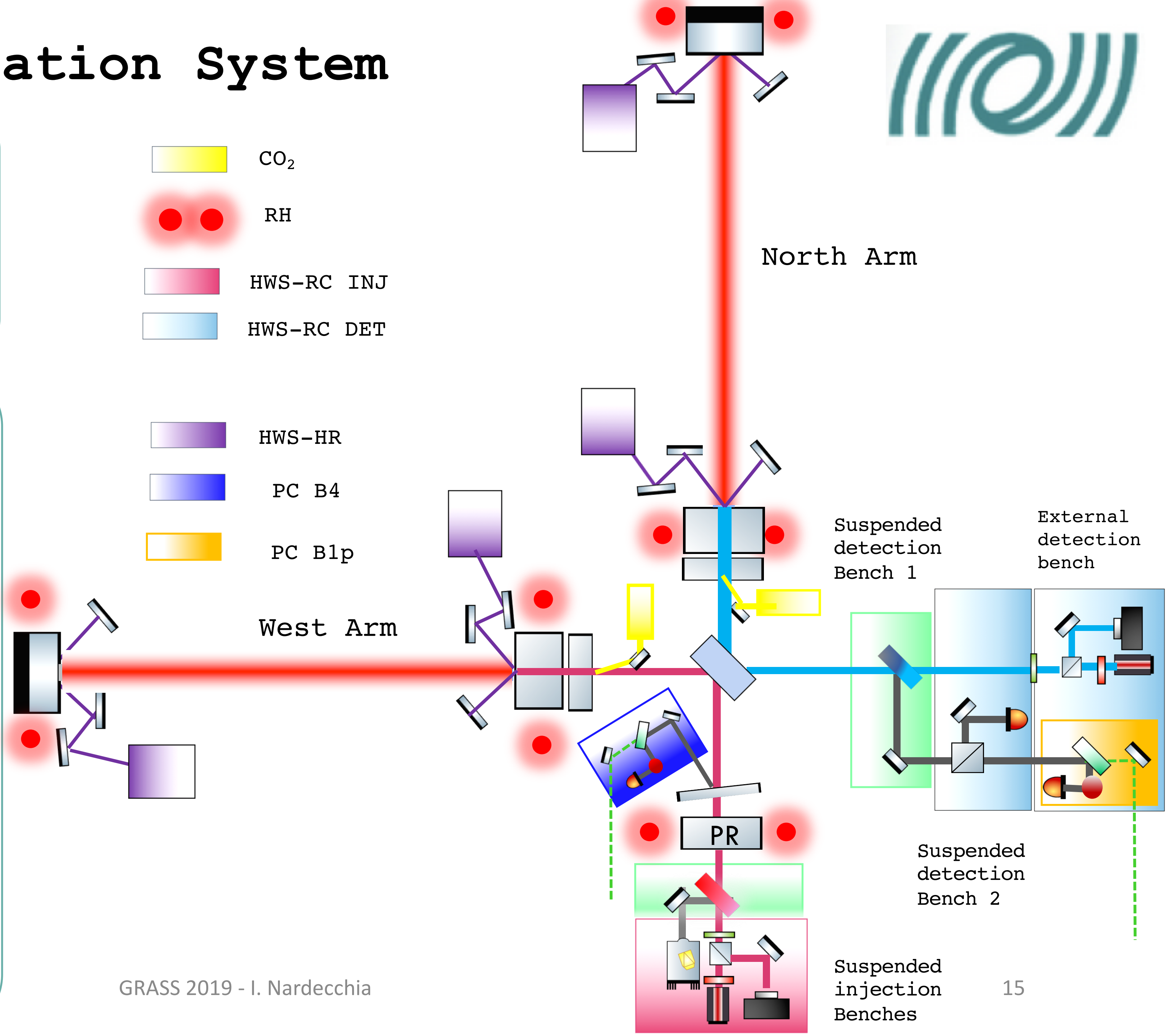
- Ring Heater (**RH**) acts on the thermoelastic deformation of the HR surface.

TCS sensors :

- Hartmann Wavefront Sensor in the recycling cavity (**HWS-RC**): to measure the thermal lensing;
- Hartmann Wavefront Sensor on the HR surface (**HWS-HR**): to measure the thermoelastic deformation of the HR surface;
- Phase cameras (**PC**) developed by Nikhef Group : to sense independently the carrier and sidebands in the PRC and on the DP.

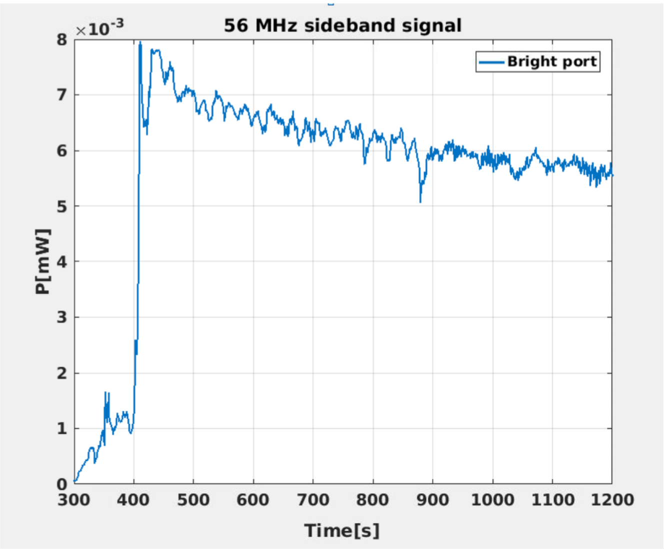


ITF + TCS

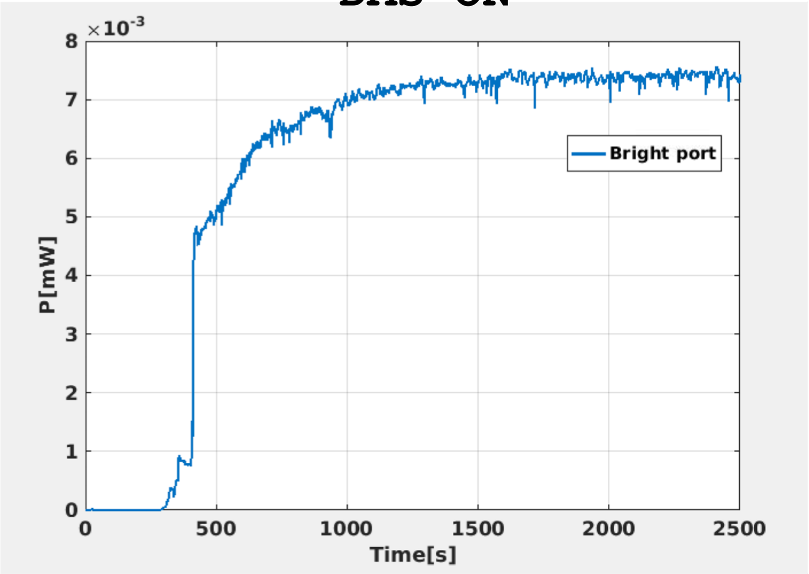
- Behaviour of ITF control signal whith TCS ON and OFF

DAS restores the recycling cavity gain.

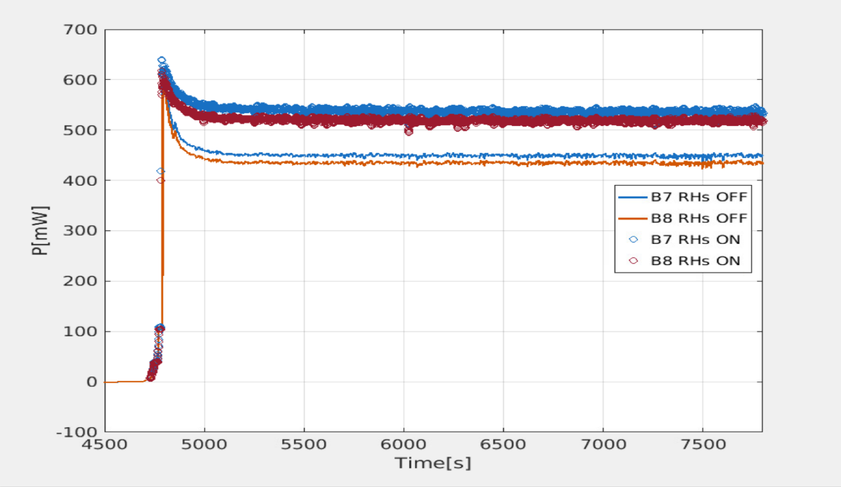
DAS OFF



DAS ON



Power transmitted by ETM



What we learned during O3

Actuators

- When ITF cools down relocking is more difficult -> CO_2 CH to keep unchanged the thermal state of the ITF during the lock acquisition

- The RH thermal constant is very long (about 10 hr)
  → Long commissioning time to fine tune the working point
  → Find a way to reduce the time to reach the steady state

- The thermal lens induced by the ITM RHs must be compensated to avoid the power loss of the sidebands circulating in the power recycling cavity
  → CO_2 CH to compensate the thermal lensing induced by RH

Sensors

- The thermal defocus of the HWS plate introduces a spourious curvature in the HWS-HR measurements which does not allow to satisfy the AdV requirements (+/-2 m)
  → HWS temperature stabilization system to remove this contribution

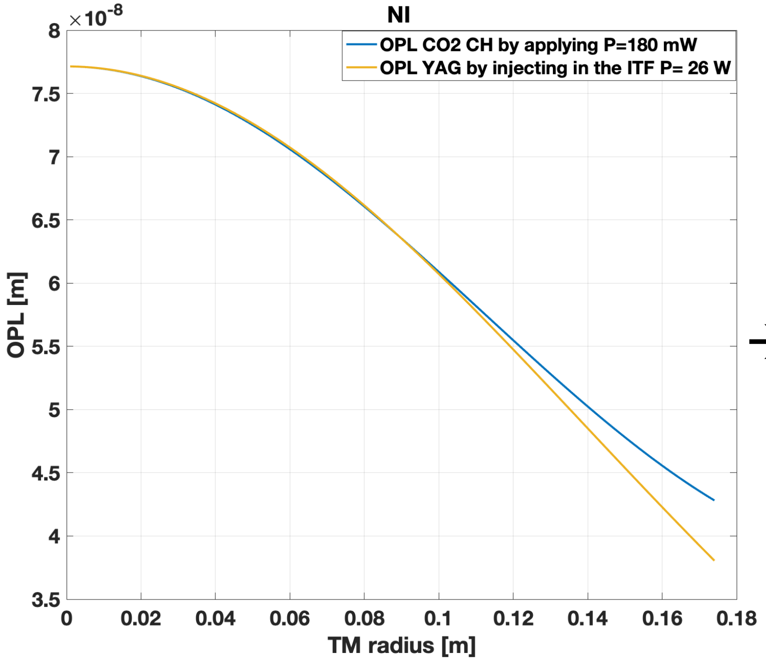
- The thermal defocus of the bench introduces a spourious curvature in the HWS-HR measurements which does not allow to satisfy the AdV requirements (+/-2 m)
  → Two color system to remove this contribution

Actuators : CO_2 CH

- CO_2 CH enganged to keep unchanged the thermal state of the when the ITF unlockes.
- CO_2 CH used to mimic the YAG effect:
  - Same beam size of the YAG on the input test masses $w_{CO2} = w_{YAG} = 49$ mm
  - The power absorbed by the ITM coatings can be calculated by using the HWS-RC absorption measurements:

  $\alpha_{NI} = [0.65 \pm 0.05]$ppm → $P_{abs,NI} = 93$ mW (for ITF input power of 26 W)
  $\alpha_{WI} = [0.36 \pm 0.07]$ ppm → $P_{abs,WI} = 50$ mW (for ITF input power of 26 W)

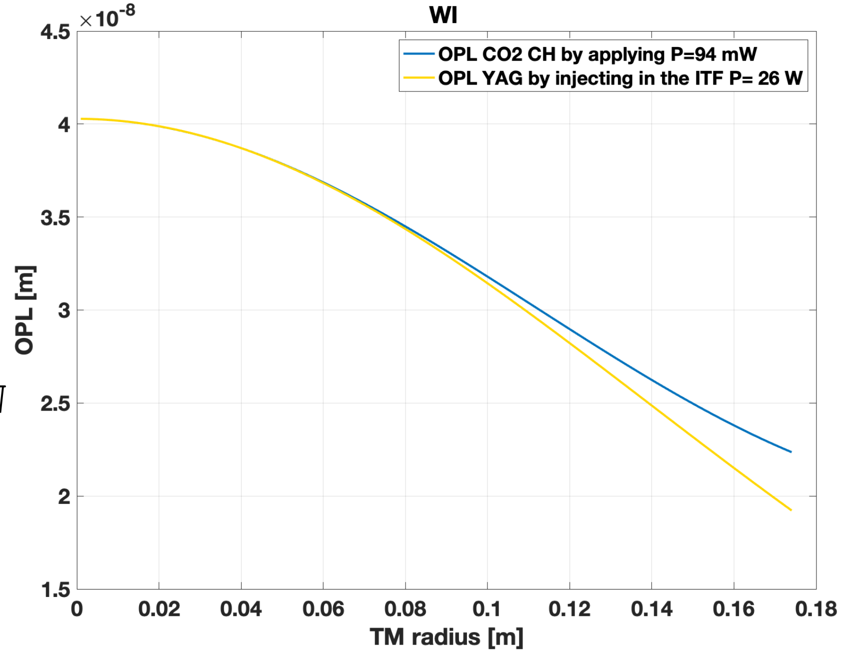
YAG Optical Path Length (OPL) for the NI



$P_{CH\ CO2,NI} \sim 180$ mW
$P_{CH\ CO2,WI} \sim 90$ mW

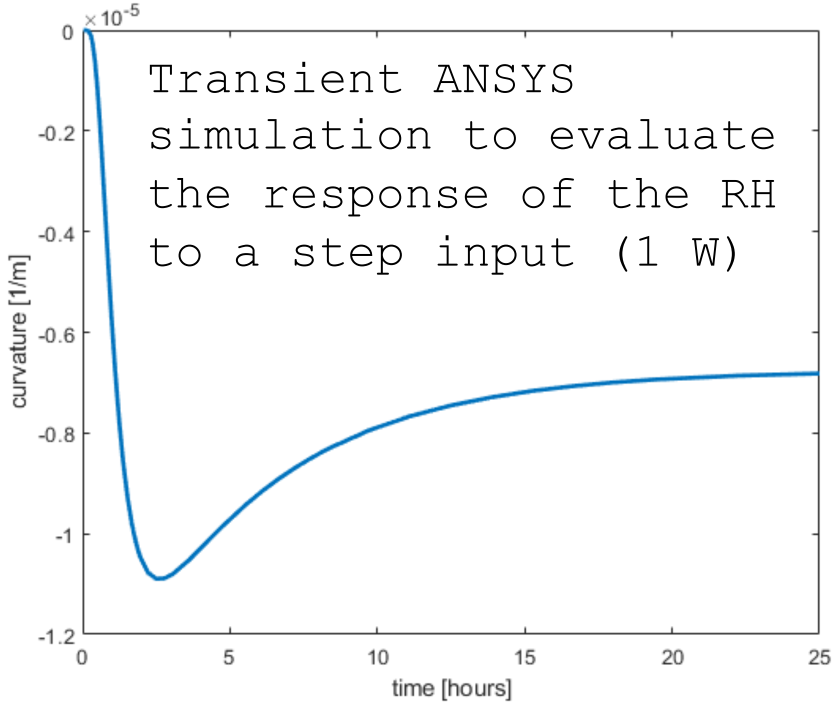
→ Successfully tested at input power of 26 W

YAG Optical Path Length(OPL) for the WI



Actuators: RH

- The RH thermal constant is very long (about 10 hr)
  → **Goal: attain regime curvature in ~ 1 hour**
- The system is considered linear to a first approximation, so that the response scales linearly with the applied power
- Radiative emission is linear considering the small increments in temperature.



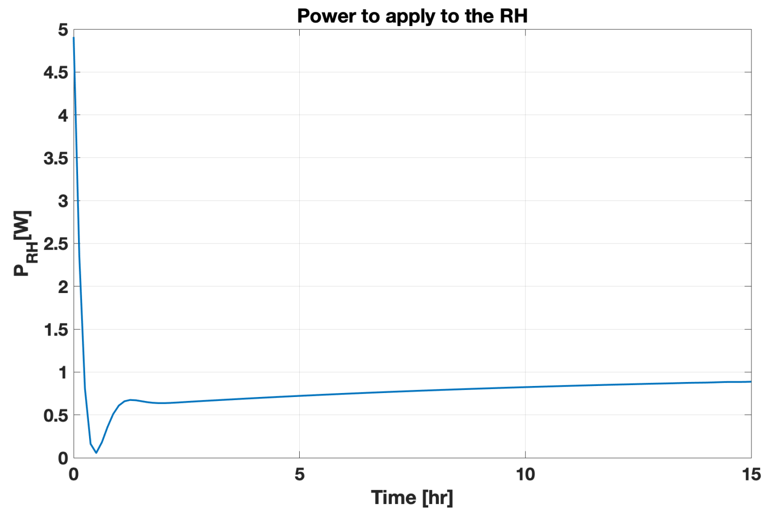
The transfer function *FT(s) in the Laplace domain is:*

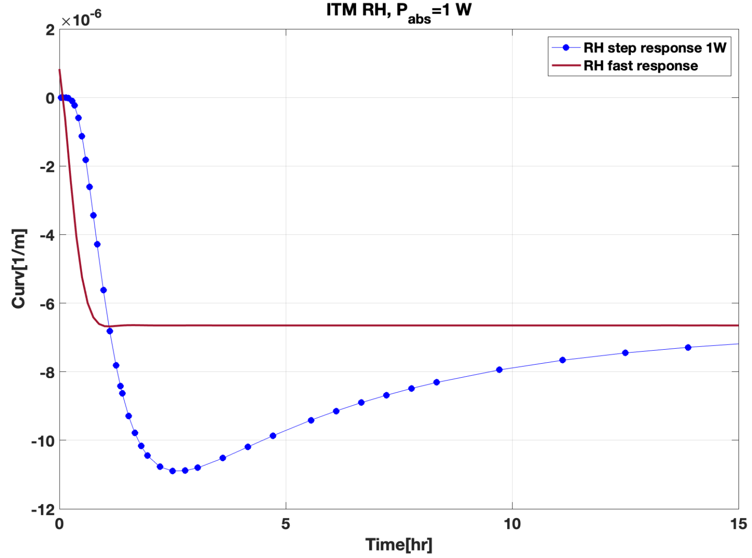
$$FT(s) = \mathcal{L}(r_\delta) = s\,\mathcal{L}(r_\theta)$$

The response r to any input i is:

$$\mathcal{L}(r) = FT(s)\,\mathcal{L}(i)$$

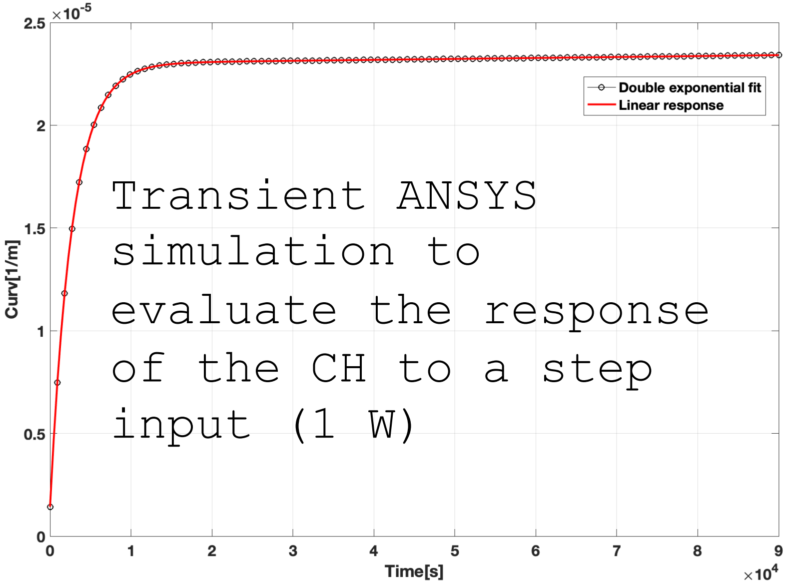
Given r(t), the input i(t) can be calculated





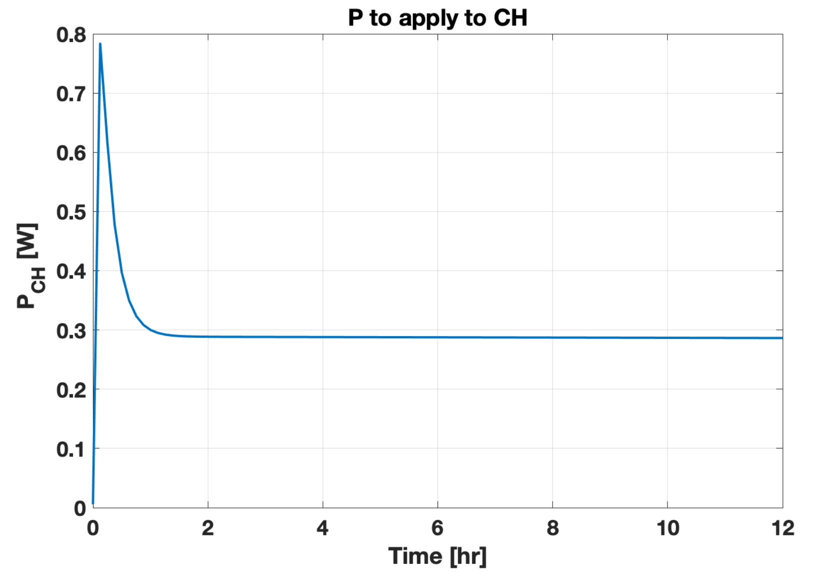
Actuators: CH + RH

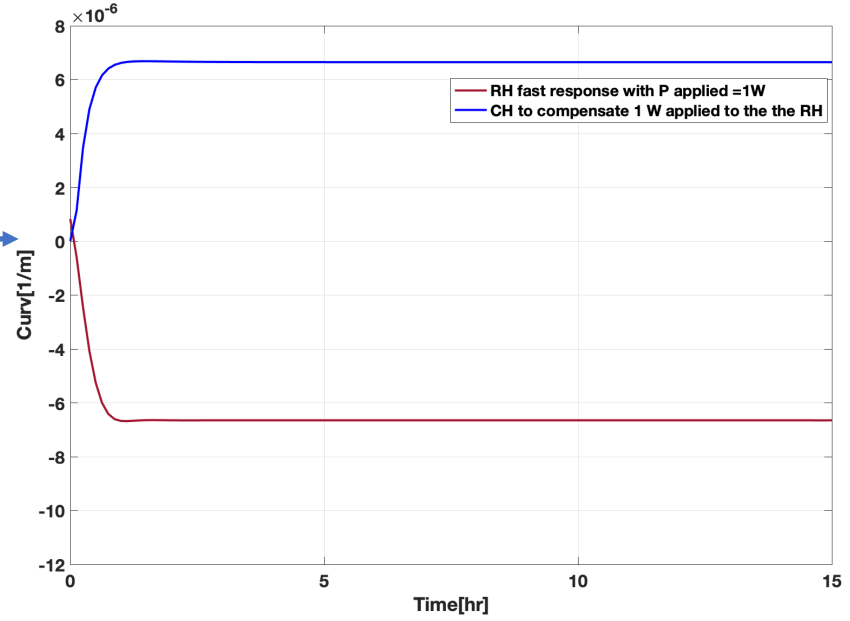
- The thermal lens induced by the ITM RHs must be compensated to avoid the power loss of the sidebands circulating in the power recycling cavity
  → CO_2 CH to compensate the thermal lensing induced by RH



Transient ANSYS simulation to evaluate the response of the CH to a step input (1 W)

By modulating the power of the RH and CH it is possible to turn on the RH without spoiling the sideband signal in the power recycling cavity.

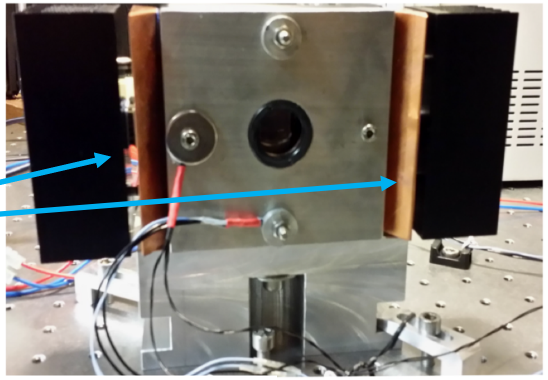




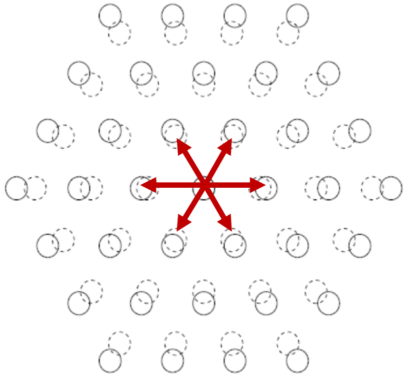
Sensors

- Thermal defocus in the HWS plate is sensitive to room temperature changes:
  ➔ T_{PLATE} must be controlled. A temperature control within a precision of 0.01 K was tested and is being implemented on AdV

- HWS maximum temperature operation 40°C
- Working temperature [30-35]°C
- Two Peltier cells to cool down the HWS
- Two thermometers installed between the CCD body and cooling fins



HWS plate holes



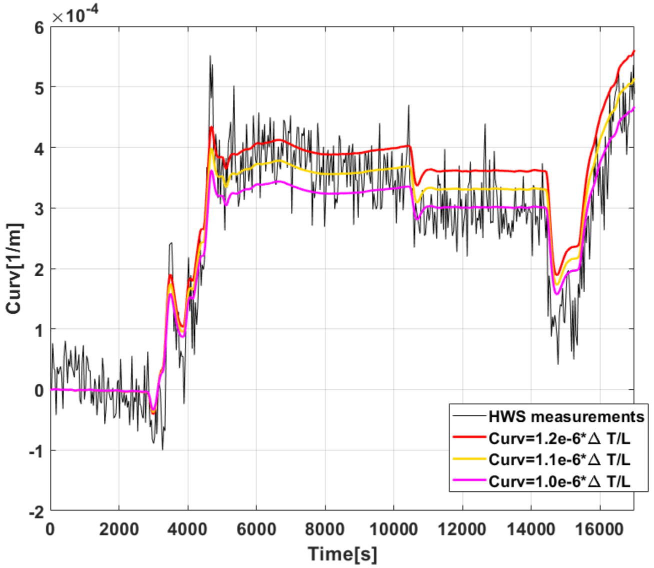
Sporious curvature introduced by the thermal defocus of the HWS plate is:

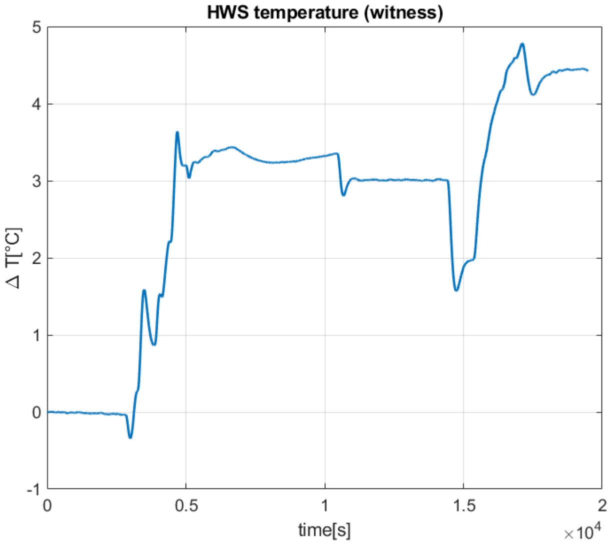
$$C = \alpha_{INV} \times \Delta T_{PLATE} / L$$

L=10 mm

$\alpha_{INV}=1.2 \times 10^{-6}$ 1/K

- Good agreement between measurements and calculations





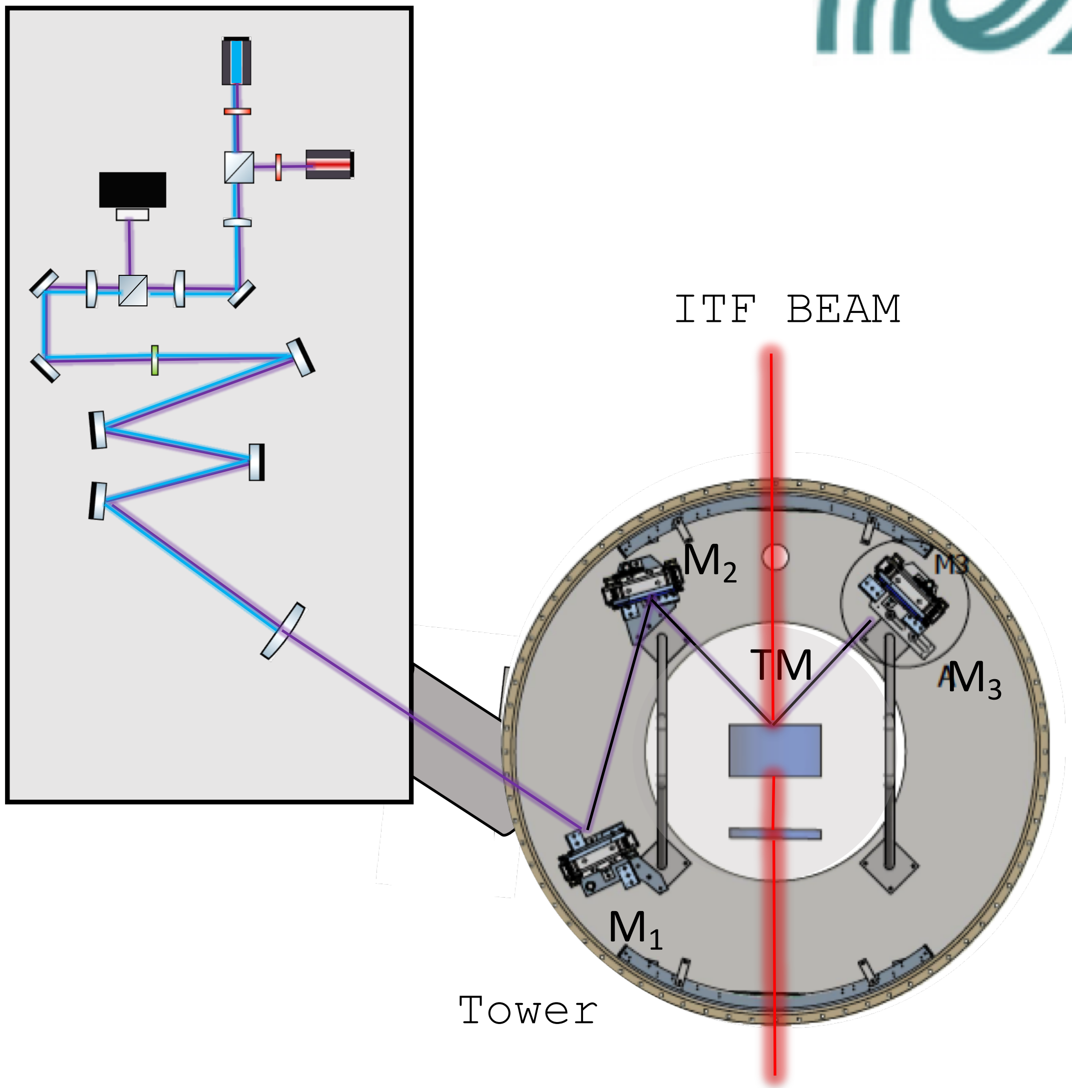
Sensors

Thermal defocus in the telescopes used to expand the HWS beam adds a spurious curvature:

➔ a secondary beam with different λ can be used to get rid of defocus (**Two colour system**)

- The thermoelastic deformation is measured by the the primary SLED beam that propagates up the HR surface (λ_1= 790nm)
- Thermal defocus is measured by a secondary beam reflected back before entering the tower (λ_2= 650 nm) and subtracted from the measurement done by the primary beam.

- This strategy is being tested in the laboratory of Tor Vergata



Conclusions

- During preparatory phase for O3, the TCS actuators have been commissioned and tuned
- TCS is currently engaged ensuring a duty cycle of the interferometer higher than 75%
- New research and development activities are being carried out in order to optimize the TCS single actuators operation and the combined action of multiple actuators to become operational in view of the next observing run (O4).