Thermal effects on the Input Test Mass (ITM) of the Einstein Telescope High-Frequency arm

EINSTEIN TELESCOPE

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ET-HF arm cavity

The Einstein Telescope (ET) High-Frequency arm will be a 10 km long Fabry-Perot cavity with an expected circulating power of 3 MW. Both input test mass (ITM) and end test mass (ETM) will be concave mirrors of Fused Silica, 620 mm in diameter, 300 mm in thickness, with radii of curvature of 5070 m. The cold cavity will have a g-factor of 0.95, a finesse of 888, a gain of ~555. The TEM00 laser beam wavelength will be 1064 nm and the beam size (waist) on the test masses will be 0.12 m.

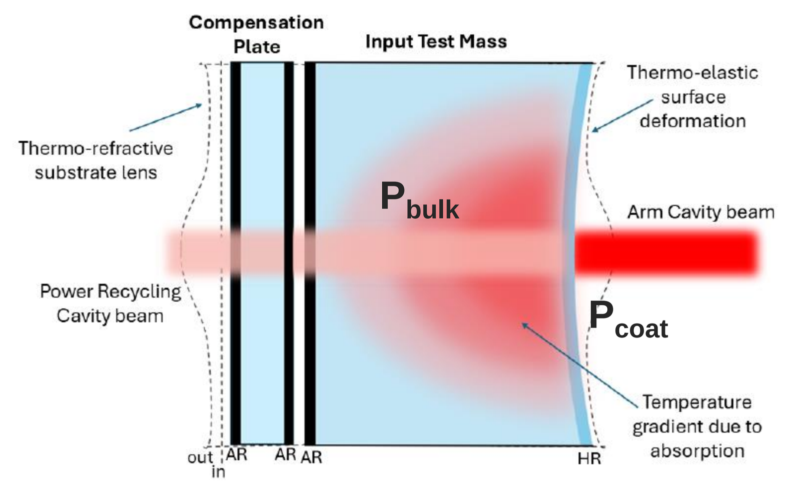
THERMAL ISSUES

Wavefront distortions and losses in the hot cavity are caused by the not-negligible power absorption of both mirror High-Reflective (HR) coating and substrate (bulk):

- HR coating absorption → Thermo-elastic deformations → Change in HR-surface sag & Change of HR-surface RoC → OPD
- Bulk absorption → Thermal gradients → Refractive index gradients → OPD (thermal lensing)

Thermal compensation systems have been introduced in the recent upgrades of the GW interferometers LIGO and VIRGO [1] :

- RoC control → Radiative heaters (RH) positioned around the test masses
- Thermo-elastic and thermo-optic effects compensation → Laser actuation acting on a compensation plate placed before ITM



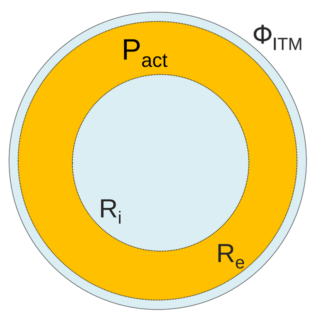
SIMULATIONS

The steady-state thermal equation for ET-ITM has been resolved, with and without the laser compensation pattern (no RH):

- Analytically (Hello-Vinet model [2]) → faster, flexible, small ΔT
- FEM (*Ansys*) + post-process (*SigFit*) → slow, more complete

The results from both methods are in good agreement.

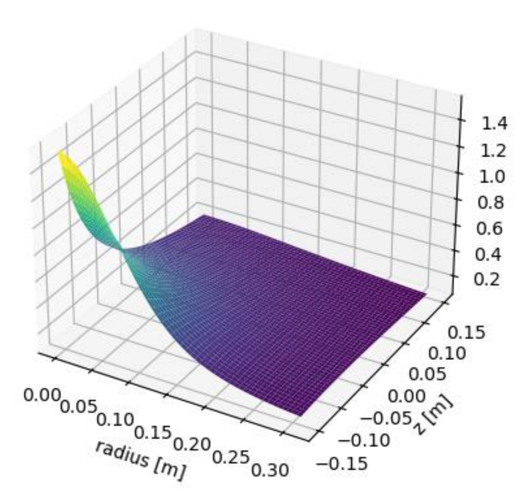
The analytical solution is useful to identify the best combination of parameters for the **compensation** (laser power, ring inner and outer radii), then FEA are performed to confirm the compensation adequacy. In a later stage the suitability of the compensation will be also evaluated with the code *OSCAR* [3] .



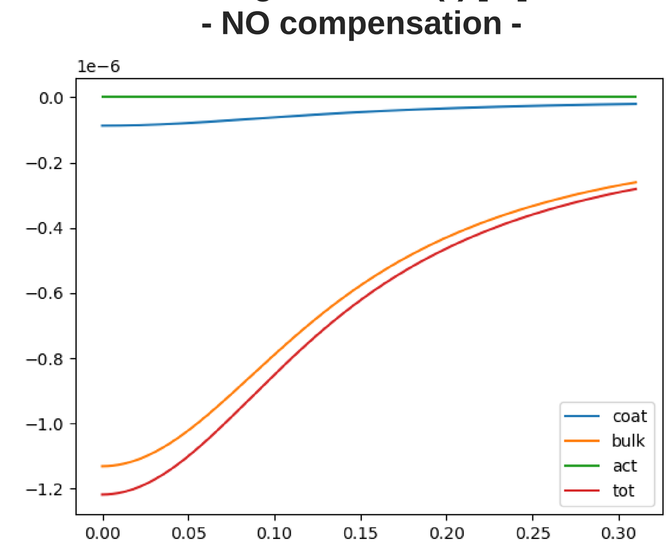
Main parameters used for simulations [4]			
n	1.45	*h (conv)*	1÷2 W/m^2K
dn/dT	$-8.5 \cdot 10^{-6}$ K^{-1}	T_{in}	290 K
α	$3.9 \cdot 10^{-7}$ m^{-1}	P_{coat}	3 MW
K	1.4 W/mK	P_{bulk}	20 kW *
ε	0.9	* Overestimated by a factor > 2	

HELLO-VINET

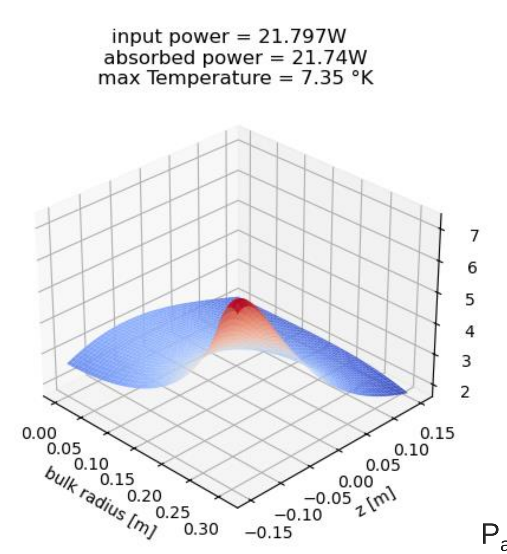
Temperature raise ΔT(r,z) [K] - NO compensation -



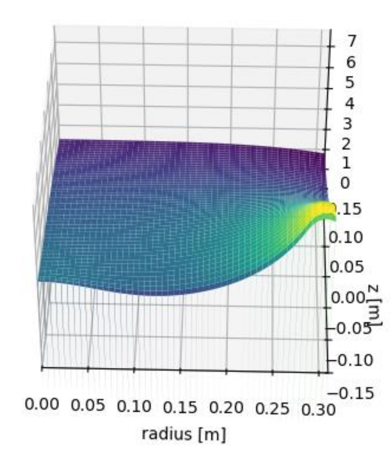
Integrated OPD(r) [m] - NO compensation -



Temperature raise ΔT(r,z) [K] due to compensation

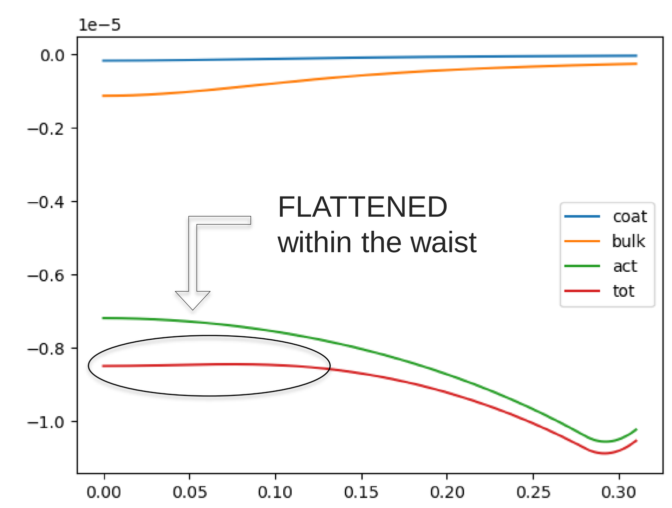


Total Temperature raise ΔT(r,z) [K] - with compensation -



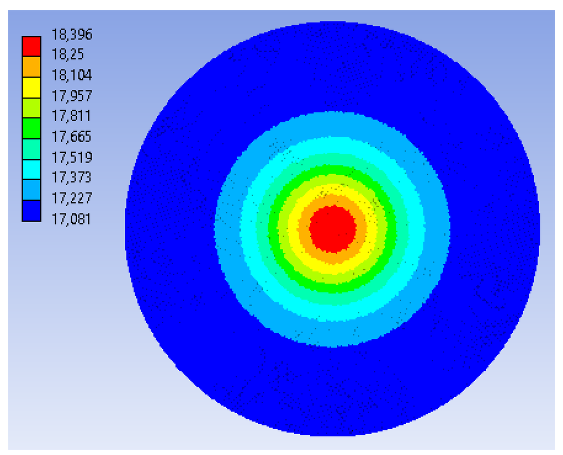
P_{act} ~ 22 W
R_i = 280 mm | R_e = 309 mm

Integrated OPD(r) [m] - With compensation -

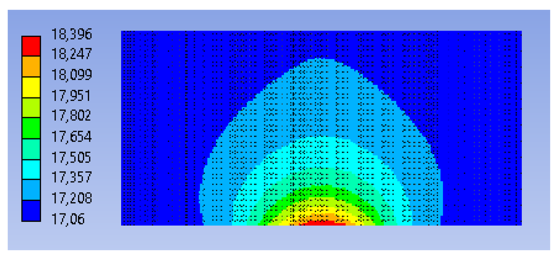


FEM

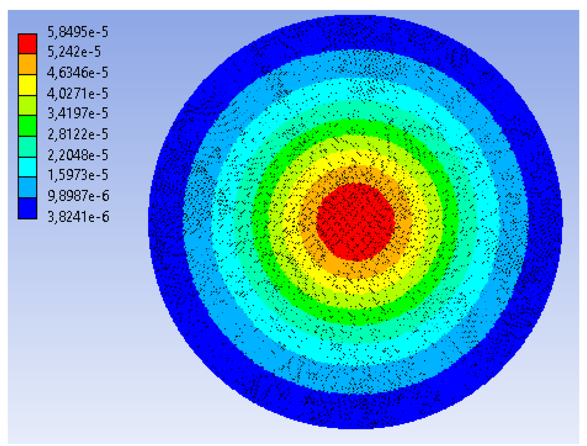
Temperature map [ºC] - HR surface -



Temperature map [ºC] - Bulk -



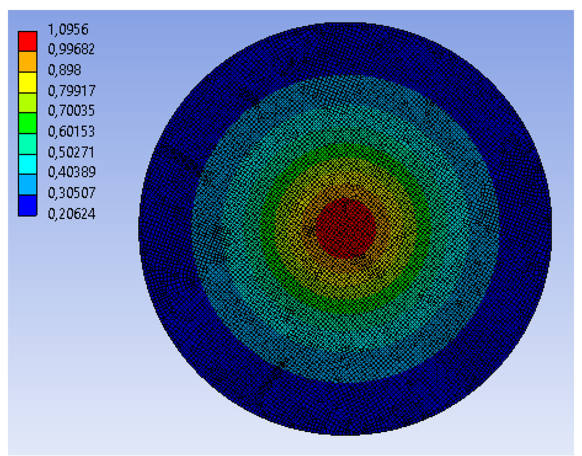
HR surface sag [mm]



Δ RoC	
Manuf.	± 10 m
Thermo-el.	+ 22 m
RHs are necessary	

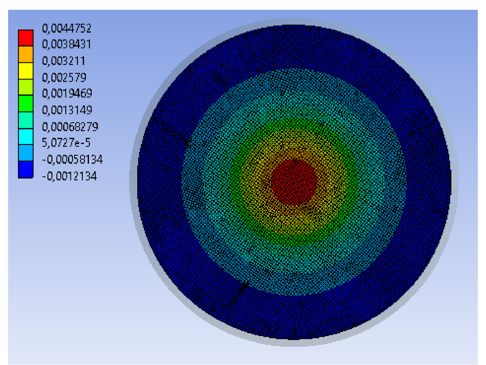
The OPD due to thermo-elastic deformations is:
2 · sag
OPD_{max} ~ 0.1 um

Integrated OPD [waves] (thermo-optic effect)

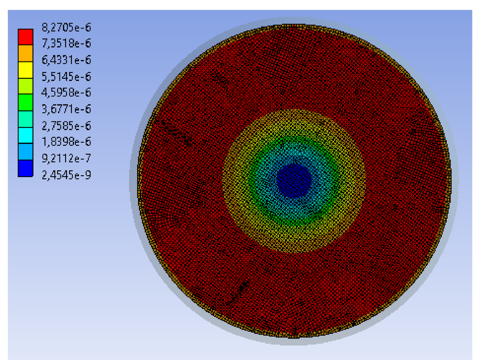


Zernike terms (rms)	
Def.	-12 nm
1st Sph	4 nm
2nd Sph	-2 nm

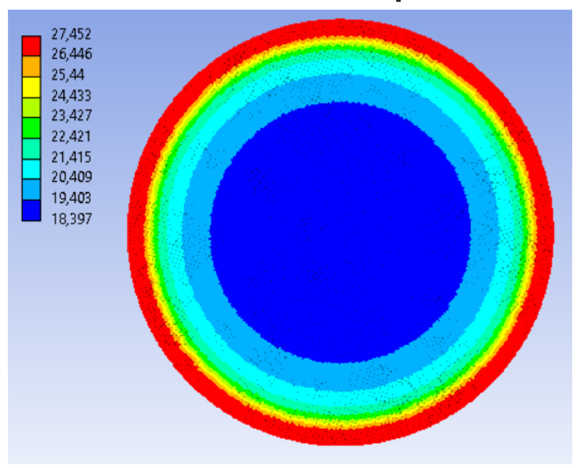
Integrated OPD [waves] (stress-optic effect)



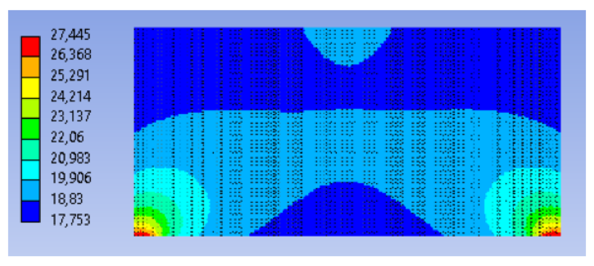
Birefringence [waves/mm] (photo-elastic effect)



Temperature map [ºC] - AR surface - with compensation



Temperature map [ºC] - Bulk - with compensation



COMMENTS

- HR coating ($Ta_2O_5SiO_2$) modeled in the FEM for stress-evaluation purposes. No appreciable changes in surface stress.
- Actuation power applied to the AR surface and completely absorbed. No compensation plate considered, RH not simulated.
- Convection present in FEM, but does not introduce significant changes with respect to analytical results.
- The general temperature raise due to the compensation makes the analytical solution less precise and reliable.

CONCLUSIONS

- ✓ **OPD due to thermo-elastic and thermo-optic effects on the ET-HF ITM preliminarily assessed**
- ✓ **OPD due to thermal stress and thermal-stress-induced birefringence effects can be considered negligible**
- ✓ **Laser actuator shape and power needed for OPD compensation preliminary assessed: ring shape with inner radius larger than the beam waist, outer radius almost equal to the mirror radius. Required heat flux on the ring: ~0.406 mW/mm^2**

References

1) Rocchi A., "Thermal Effects and Other Wavefront Aberrations in Recycling Cavities" (2014)
2) Hello P., "Compensation for thermal effects in mirrors of Gravitational Wave Interferometers" (2001)
3) Degallaix J., "OSCAR: A MATLAB based package to simulate realistic optical cavities" (2020)
4) ET Collaboration, "ET-0007B-23 Conceptual design and noise budget of Einstein Telescope" (2023)

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XV ET Symposium | 26-30 May 2025 | Bologna (Italy)

ET ITALY Einstein Telescope