GEO 600 beam splitter TCS: Status and Commissioning

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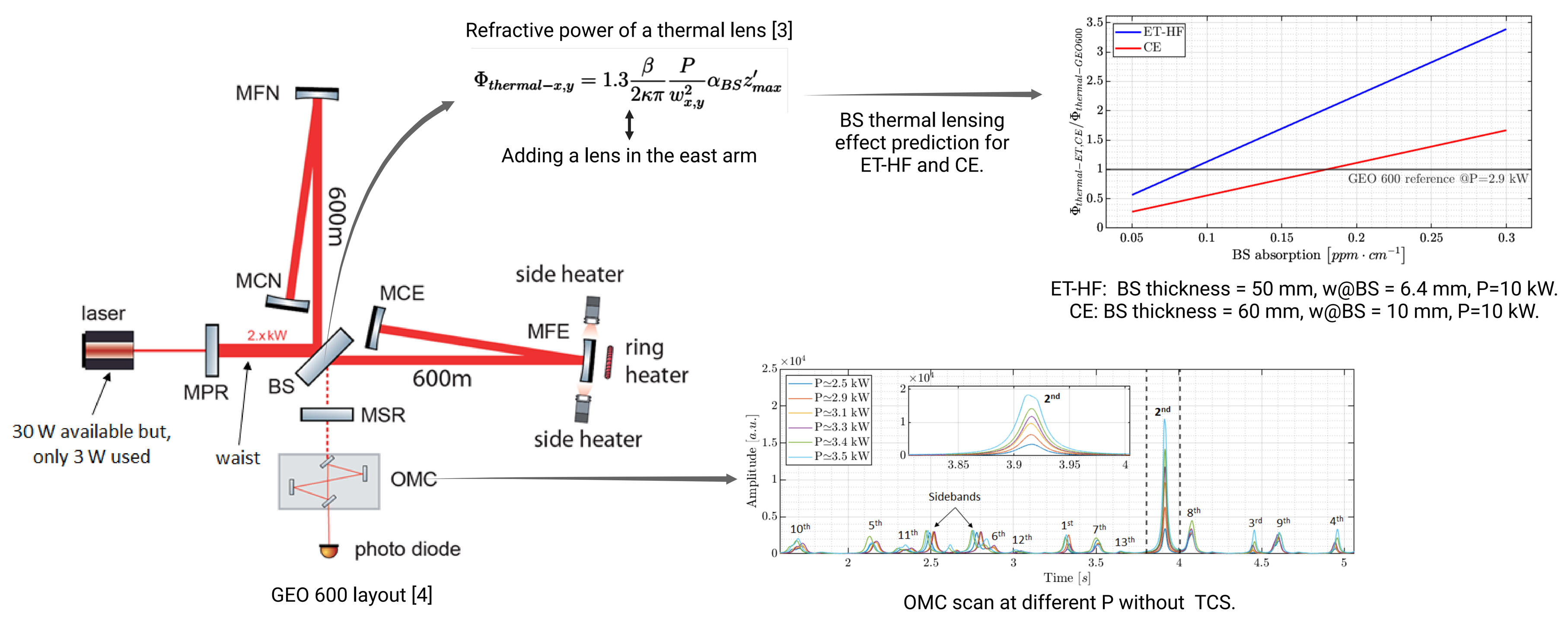
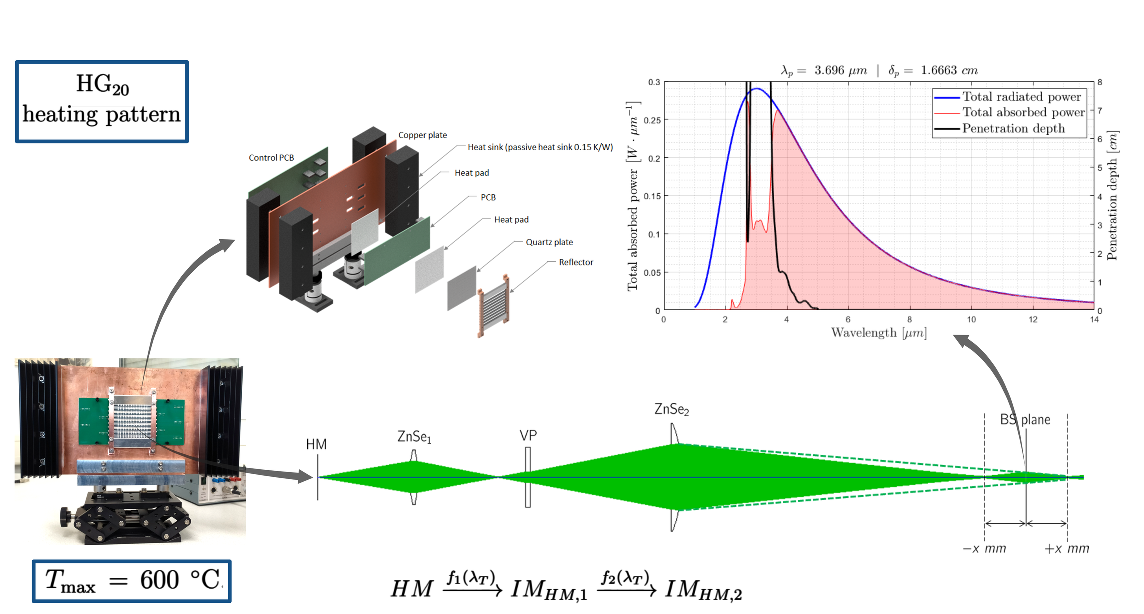
Introduction

For a gravitational wave detector to operate at its designed sensitivity, its optics must be free from imperfections such as thermal lensing. In GEO 600, the beam splitter (BS) experiences a strong thermal lensing effect due to the high power build-up in the Power Recycling Cavity (PRC) combined with a tiny beam waist. This results in the fundamental mode being converted into higher order modes (HOMs), which subsequently affects the performance of the detector. This issue, which has so far mainly affected GEO 600, will be generalised to the third generation of gravitational wave detectors, namely the Einstein Telescope HF (ET-HF) [1] and the Cosmic Explorer (CE) [2], which will operate with approximately 10 kW laser power at their beam splitters with relatively small beam sizes. To overcome this problem, GEO 600 uses a Thermal Compensation System (TCS) applied to its BS. It involves projecting a spatially tunable heating pattern through an optical system onto the beam splitter. The main objective of this system is to mitigate the thermal lens effect and restore the detector to its ideal operating state.

BS thermal lensing effect in GEO 600



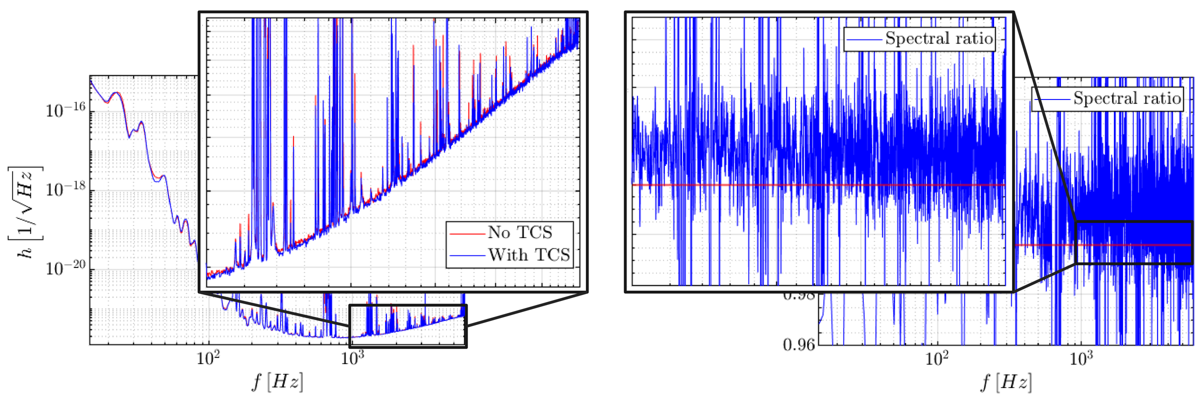
The GEO 600 TCS



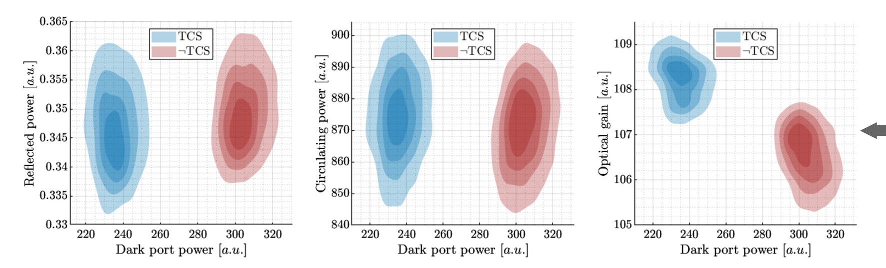
Equation for Magnification (Mag) and Defocus (Def) tuning.

- Heater Matrix:
  - Good thermal insulation.
- Optical system:
  - Better NA.
  - Mag and Def tuning.
  - Remotely controlled.
- Power up investigation possible.

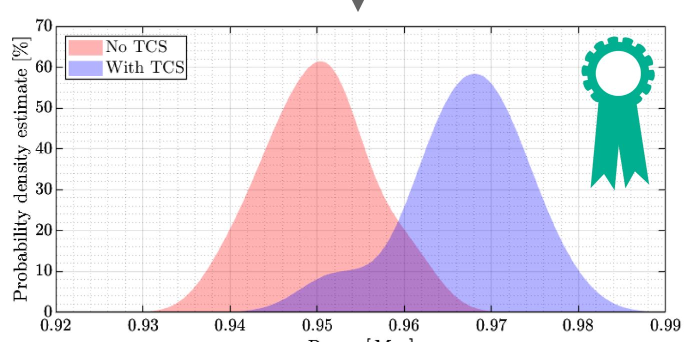
TCS optimisation at P = 2.9 kW without SQZ, effect in h



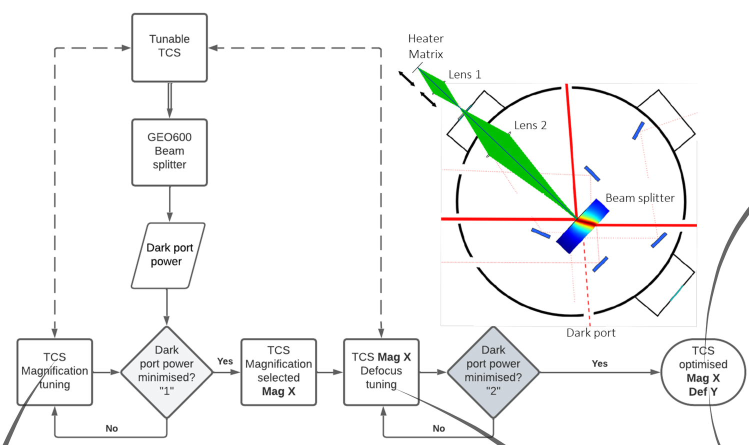
Left: GEO 600 strain sensitivity with and without TCS - Right: The corresponding spectral ratio.



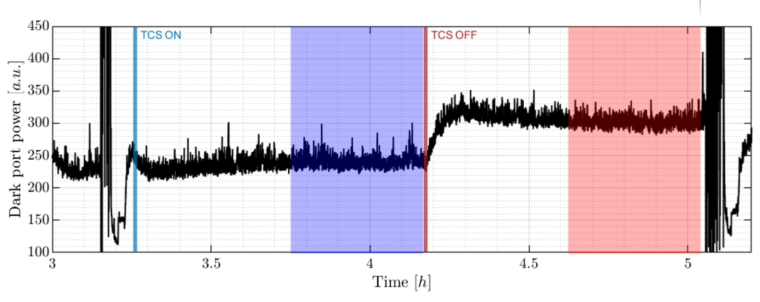
2D KDE of the MPR reflected power, the circulating power and the optical gain of GEO 600. In dark red without TCS, and in dark blue with TCS.



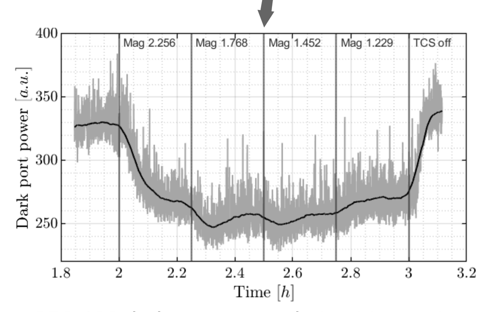
Detection range for a binary neutron star system of 1.4 solar masses each, with a SNR of 8.



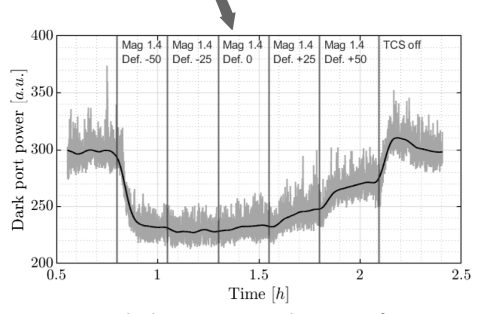
TCS optimisation flowchart at P = 2.9 kW.



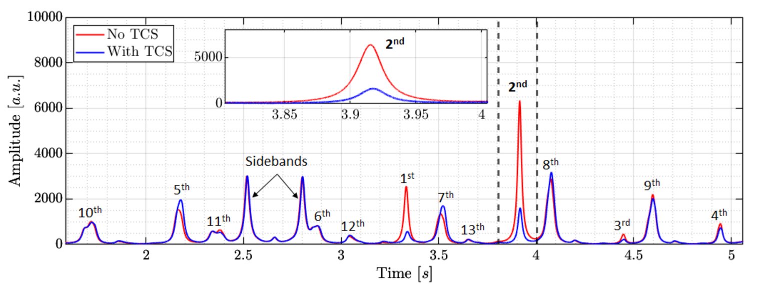
GEO 600 dark port power at P = 2.9 kW, with and without TCS.



GEO 600 dark port power during Mag tuning

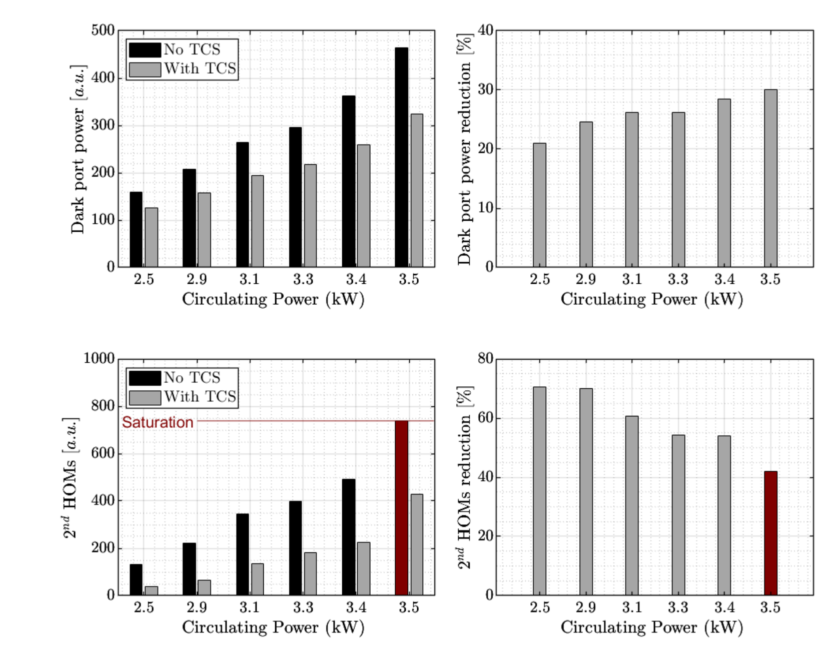


GEO 600 dark port power during Def tuning



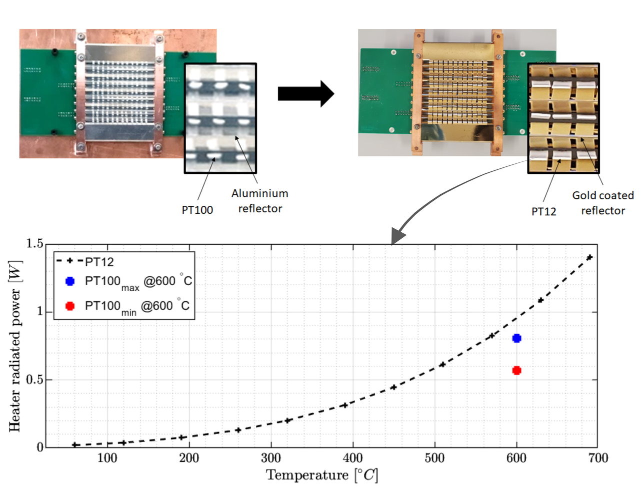
OMC scan at P = 2.9 kW with TCS.

TCS at higher power



These plots show the dark port power and the 2nd HOMs content with and without TCS (optimised for P=2.9 kW) for different P in the first column. In the second column, we have the corresponding reduction rate. We achieved a 50% to 70% reduction of the 2nd HOM content. The current TCS allows operating at high power while keeping the HOMs as low as in nominal operating power. For instance, operating at P=3.4 kW with the TCS is equivalent to operating at P=2.9 kW without the TCS, which has been our default configuration until now.

Perspective



- Install the new heater matrix:
  - PT100 replaced with PT12.
  - PT12 produces 73% to 145% more P_{rad}.
  - HM equipped with gold coated reflector.
- Power up:
  - Iteratively optimise the TCS at different P.
  - Tuning the control loops involved in locking GEO 600.
  - Understanding and effective mitigation of power-up challenges.

Conclusion

We have successfully developed and implemented a tunable TCS to counteract the thermal lensing effect in the GEO 600 BS. Selecting the correct magnification factor and defocus is crucial to ensure an even heat distribution of a given pattern at the BS. The compensation method has proven to be highly effective in reducing unwanted higher-order modes by up to 30% at high circulating power P=3.5 kW. At nominal power P=2.9 kW, we achieved an 18 kPc improvement in detection range for a binary neutron star system of 1.4 solar masses each, with a signal-to-noise ratio of 8. It is worth noting that the TCS does not introduce any noise in the strain sensitivity during operation, making it a reliable and accurate technique. Furthermore, it could very well be used in other gravitational wave detectors, in particular in third-generation detectors such as the Einstein Telescope (ET) and the Cosmic Explorer (CE), where the thermal lensing effect at their BSs is expected to be especially strong.

References:
[1] Abernathy, Matthew, et al. "Einstein gravitational wave Telescope conceptual design study." (2011).
[2] Hall, Evan D. "Cosmic explorer: A next-generation ground-based gravitational-wave observatory." *Galaxies* 10.4 (2022): 90.
[3] Bogan, Christina, et al. "Novel technique for thermal lens measurement in commonly used optical components." *Optics Express* 23.12 (2015): 15380-15389.
[4] Wittel, Holger. Active and passive reduction of high order modes in the gravitational wave detector GEO 600. Gottfried Wilhelm Leibniz Universität Hannover, 2015.