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Controlling Transient Thermal Effects in High-Power Gravitational-Wave Detectors

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LIGO Scientific Collaboration

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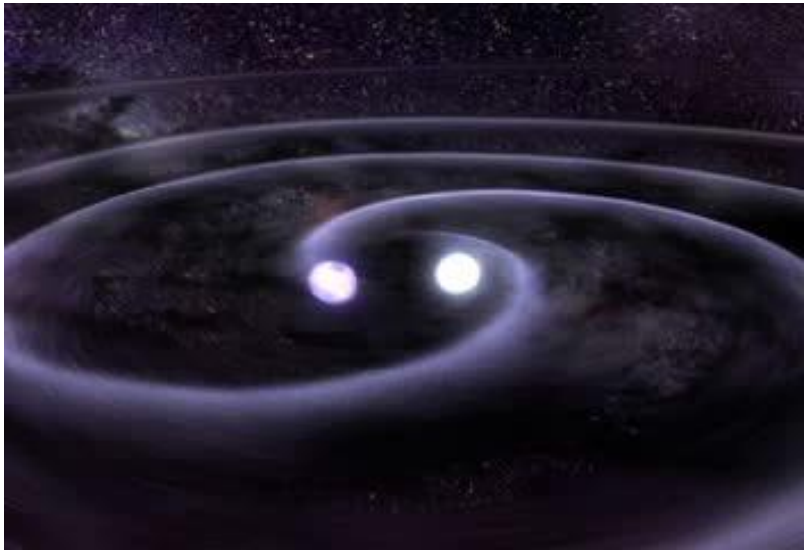
Presentation Outline

- Why high power?
- Transient thermal effects
- The TCS
- Controlling thermal effects
- Models
- Results

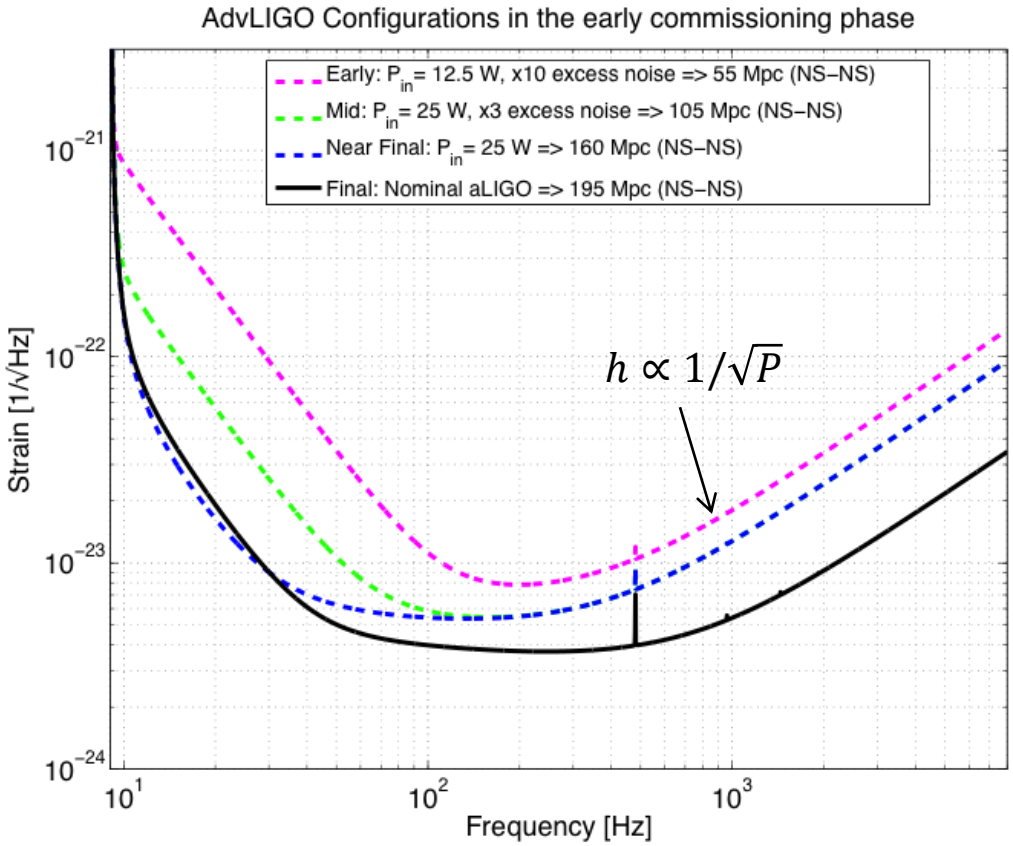
Why high-powered laser operation?

- High-frequency gravitational-wave emitters (like compact binary mergers) could reveal interesting physics we don't fully understand yet.
- However, detecting high-frequency waves requires overcoming fundamental noise sources that affect the signal.



Credit: NASA / Goddard Space Flight Center

Why high-powered laser operation?



- Above ~150 Hz, Advanced LIGO's noise floor is dominated by quantum shot noise.
- Increasing the laser power increases strain sensitivity, but causes self-heating in the test masses that must be addressed & controlled.

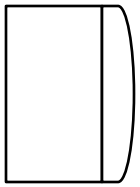
Transient thermal effects

Thermoelastic effects

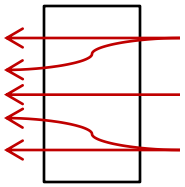
- Occur as a result of thermal expansion.
- These lead to surface deformations in the test-mass.

Thermorefractive effects

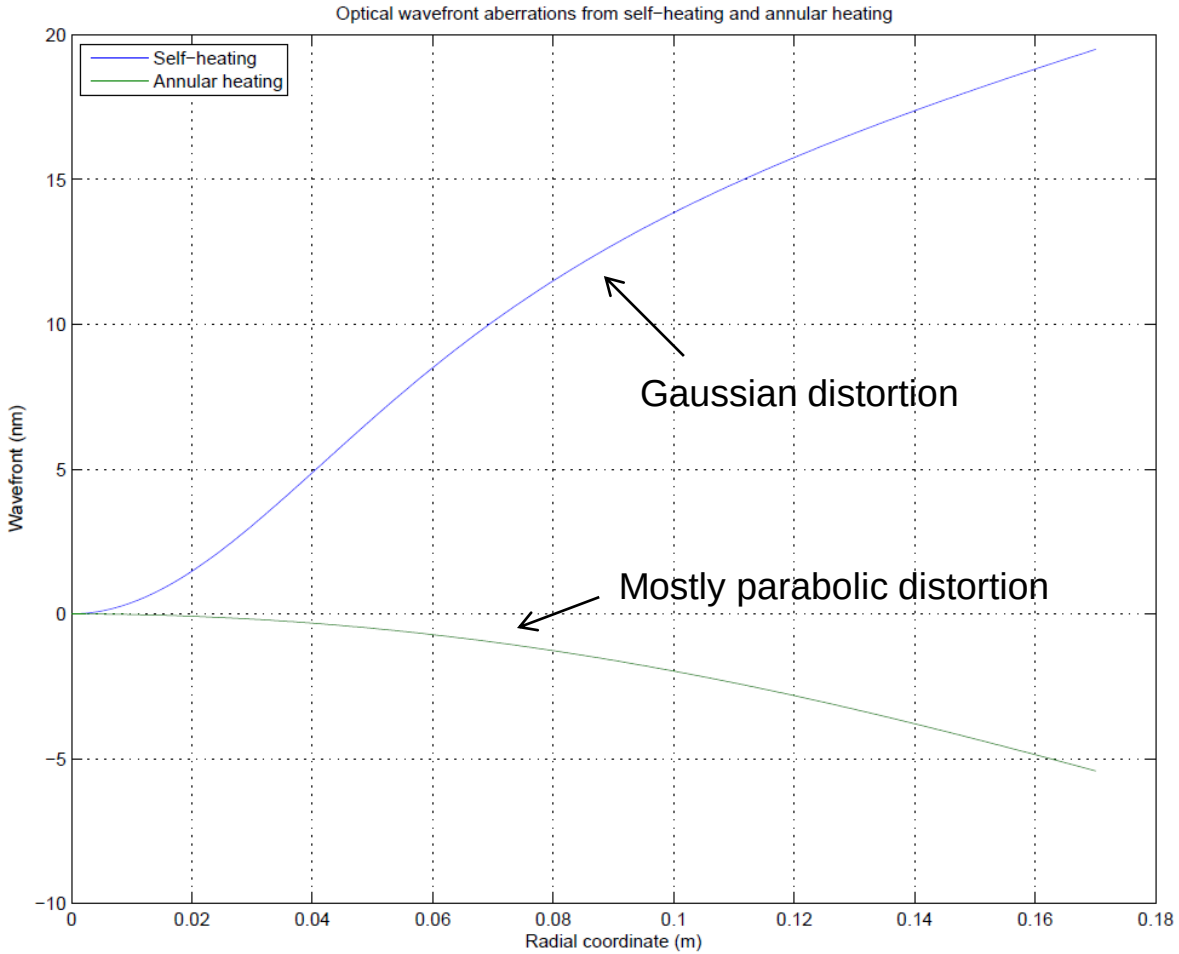
- Occur as a result of the thermo-optic effect.
- These lead to spatially-dependent refractive indices.



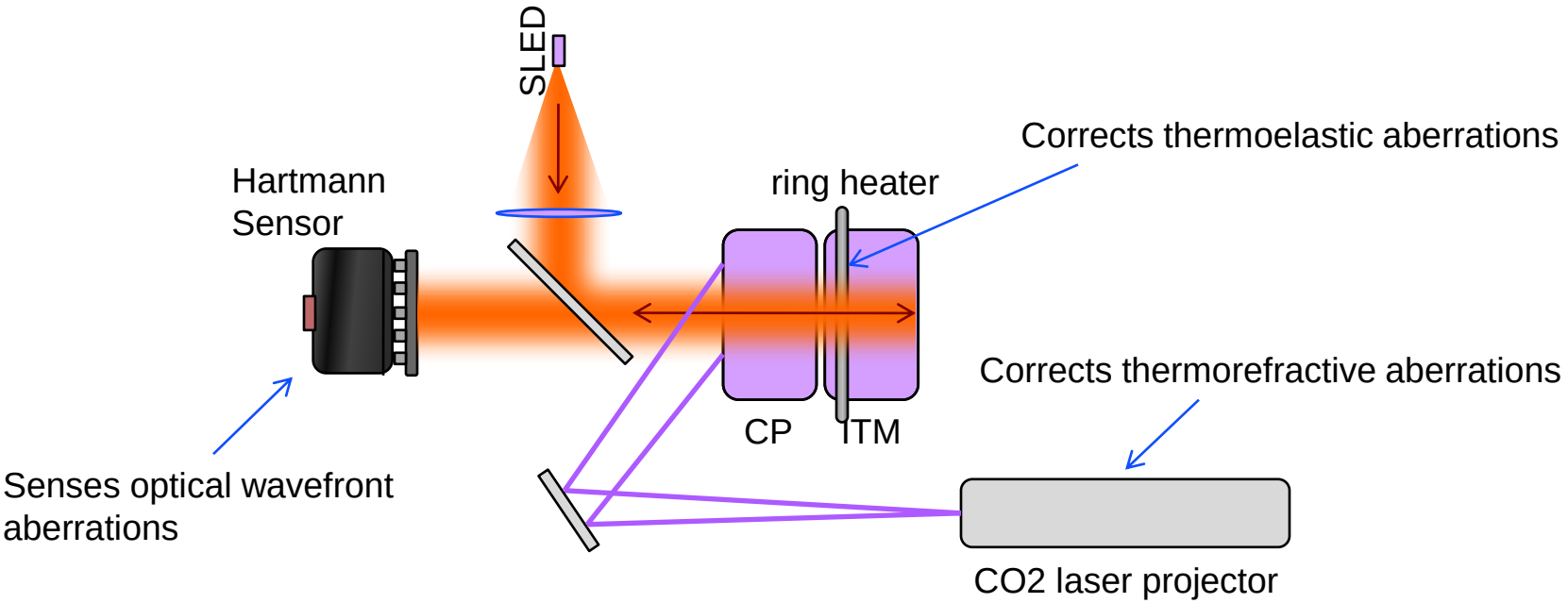
Both induce optical wavefront aberrations.



Characterizing optical aberrations



The TCS: A Diagram



Credit: Dr. Aidan Brooks

TCS controller model

- A PID (proportional-integral-derivative) controller model was developed in MATLAB using finite difference methods to minimize optical aberrations.
- The controller reads an error signal (the defocus) and calculates an actuation (emitted power) which is determined by the given controller gains.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d(e(t))}{dt}$$

Power to be emitted

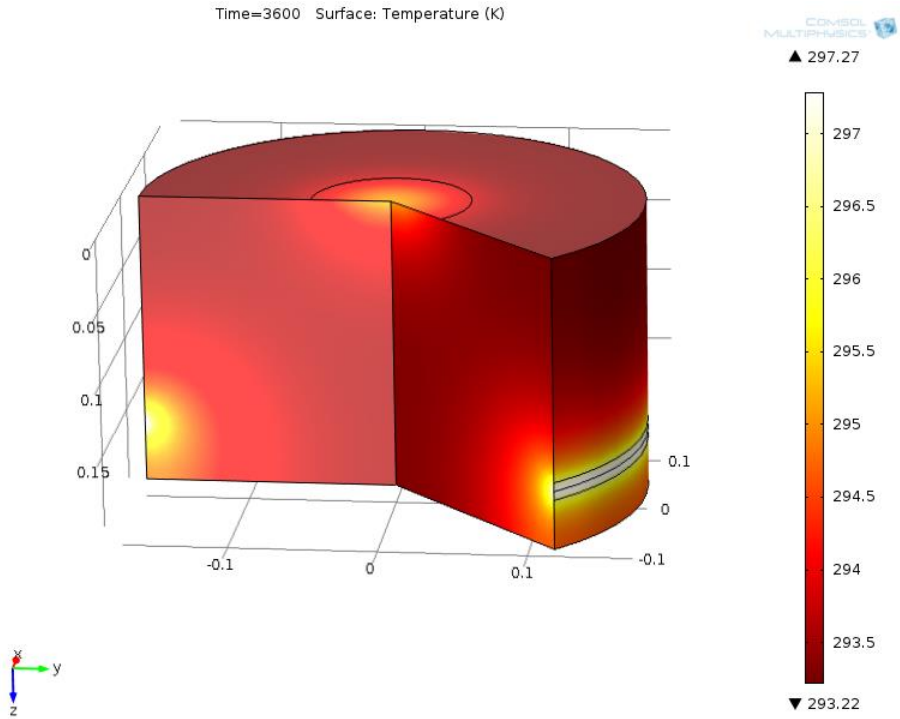
Contributes the bulk of output change

Corrects steady-state error

Decreases settling time

Finite element model

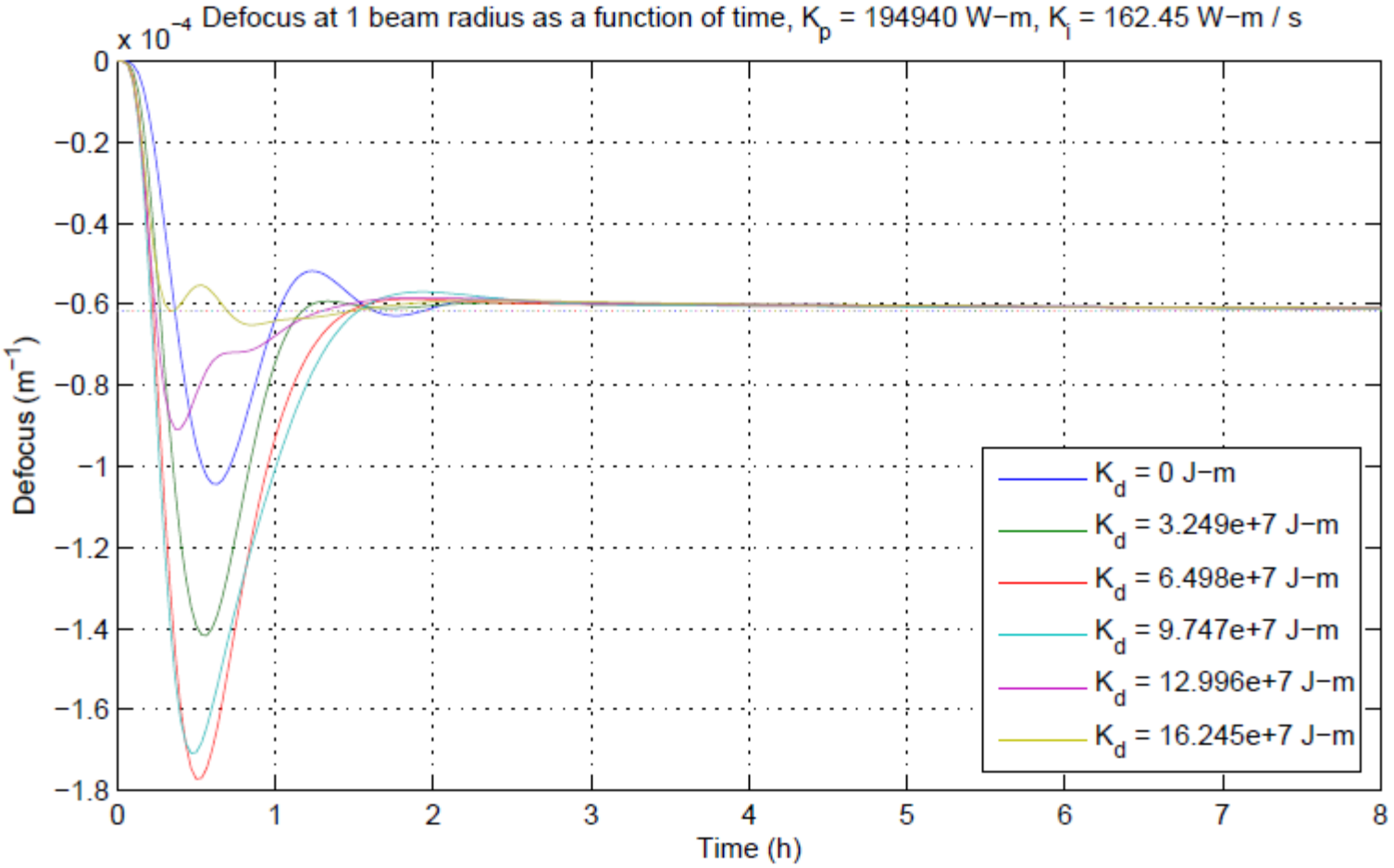
- A finite element model was developed in COMSOL to simulate the thermal effects in the ITM/ETM.
- The model includes self-heating and ring heater thermal effects.



Controlling optical aberrations

- Combining the controller model with the finite element heating model allows for a dynamic simulation of transient thermal effects in the test mass.
  - » COMSOL model simulates thermal effects in the test mass.
  - » MATLAB controller model calculates defocus & actuation.
  - » Actuation power passed to the COMSOL model; cycle repeats.
- However, communication overhead between MATLAB and COMSOL limits applicability; other methods should be tried.

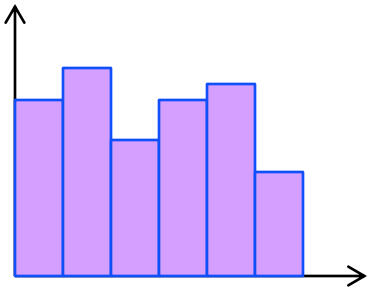
Controlling optical aberrations



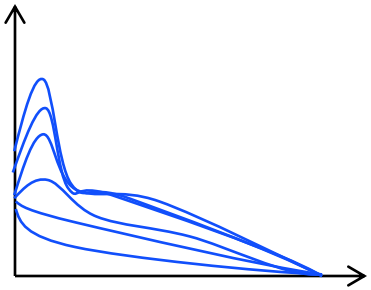
Wavefront predictor

- The predictor uses the principle of superposition and the digital nature of the actuation to recreate a digital signal response from unit rectangle signal response data.
- It does not require finite element analysis, and is extremely time-efficient (~ 300 times faster than COMSOL+MATLAB model!)
- *It approximates nonlinear thermal behavior, namely radiation, as linear.*

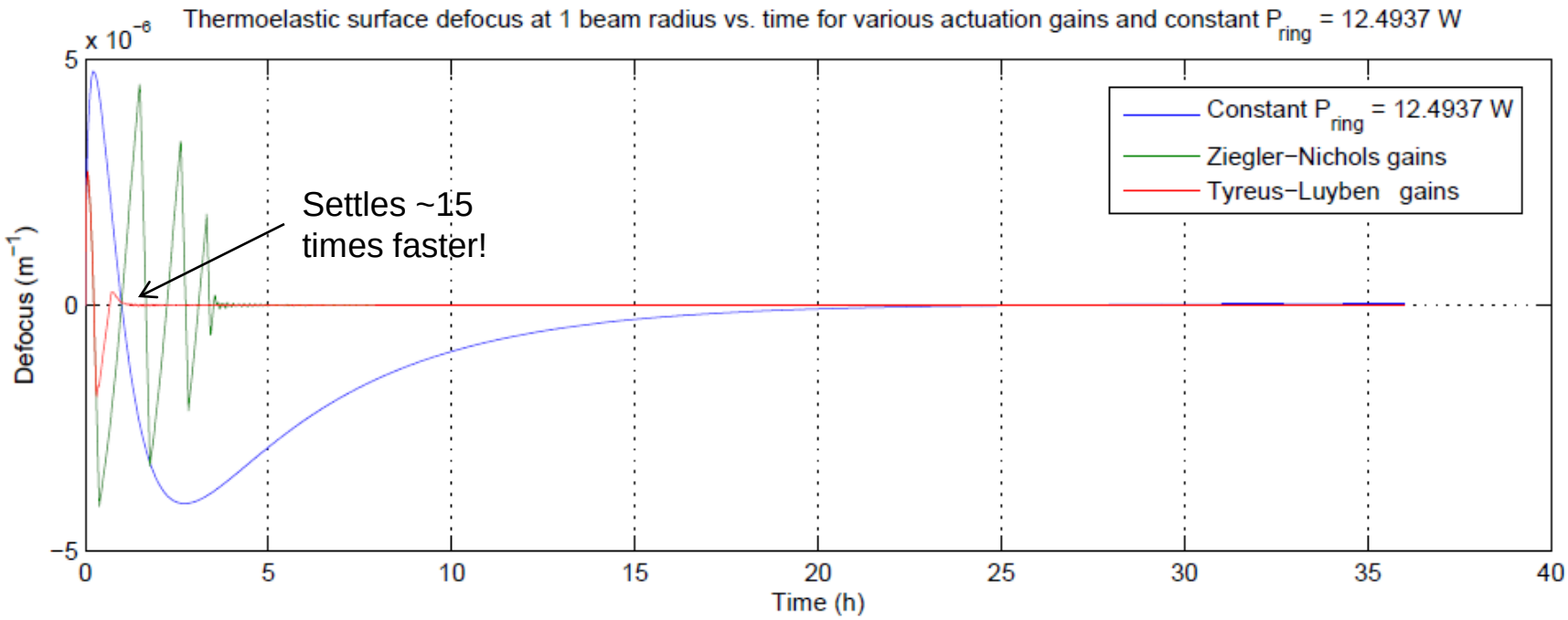
From a rectangle signal…



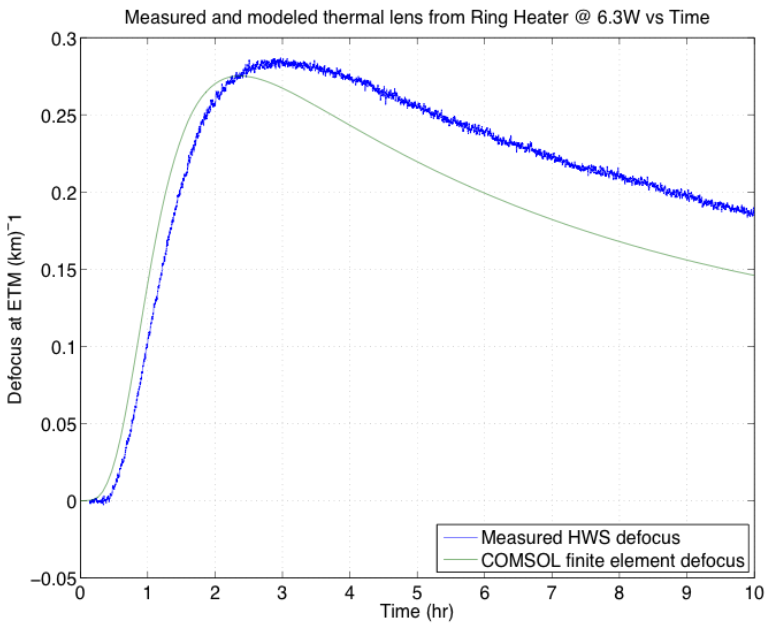
To a digital one!



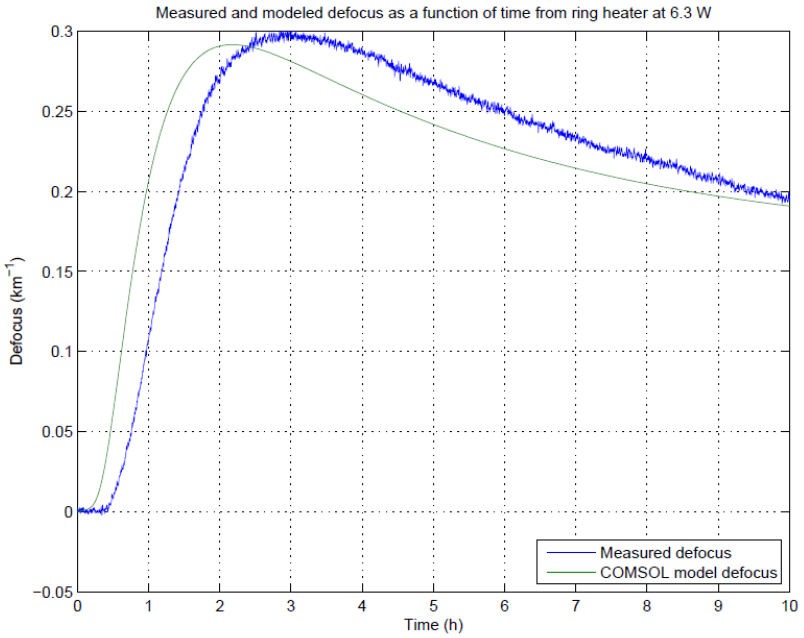
Results: Active vs. passive correction



Results: Experiment vs. Models



Aidan's model…

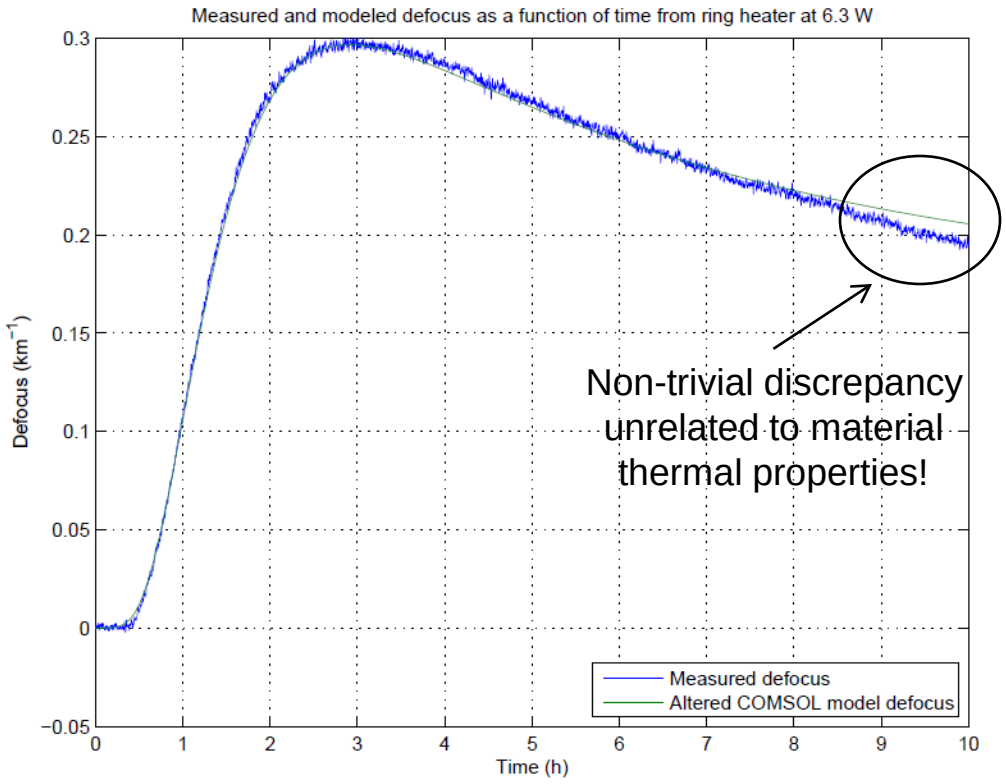


…and my model!

Both models show a similar deviation from experiment.

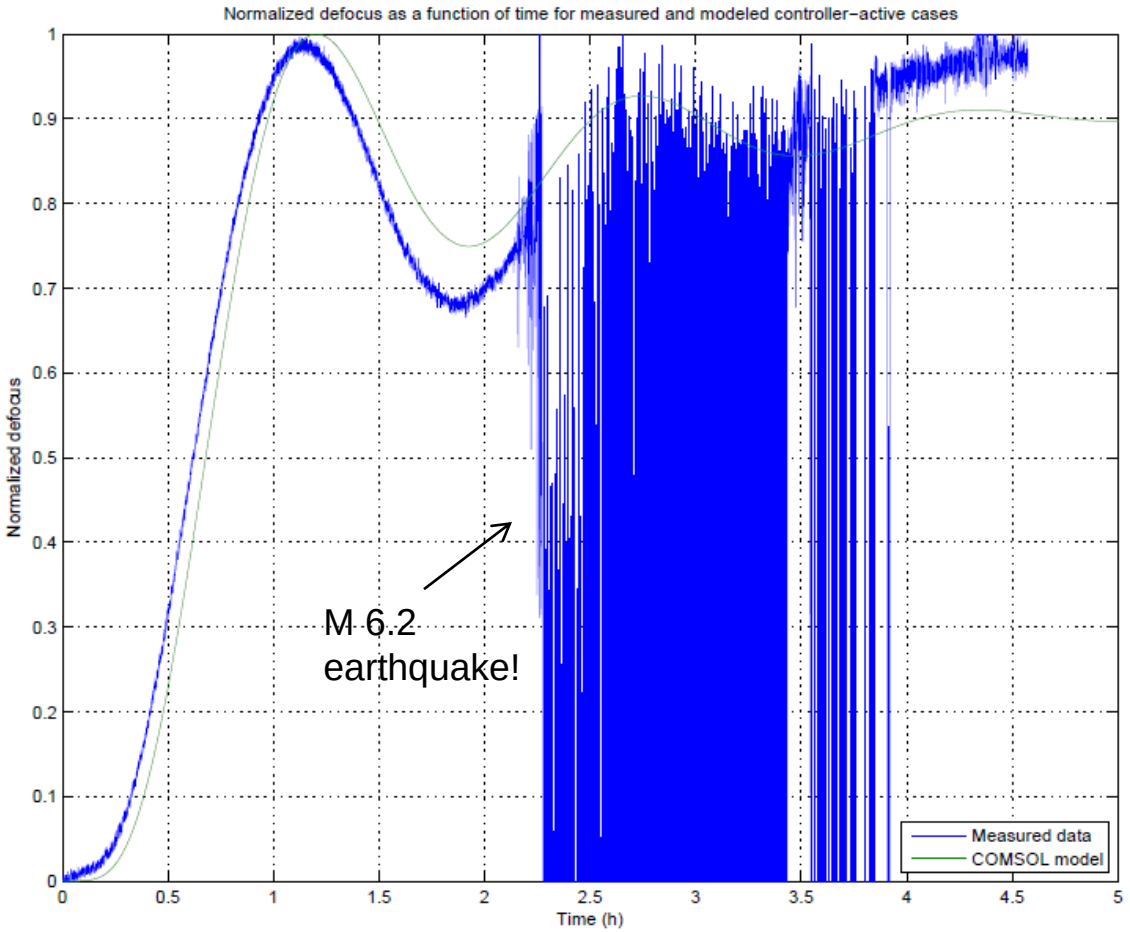
Results: Experiments vs. Models

- In an attempt to diagnose the problem, a thermal parameter study was conducted to trace the root of the discrepancy.
- By adding a turn-on time constant of ~1200 s to the ring heater and lowering the thermal conductivity ~5%, we get…



Results: Experiments vs. Models

- A full comparison was done for a controller-active case.
- Experiment appears to react quicker than the altered COMSOL model; some data corrupted from earthquake.
- Clear discrepancy: needs to be further studied.



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Future Work

- Conclusively identify source of model/experiment discrepancy.
- Include CO_2 laser projector & compensation plate into heating model; simulate full TCS.
- Quantify higher-order mode losses and compare to experiment.
- Investigate how TCS affects other control systems' performance (ACS, etc.).

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Acknowledgements

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- My fellow SURFs
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- LIGO Scientific Collaboration
- NSF

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References

1. Brooks, A., Thermal Compensation for Advanced LIGO, LIGOG1300218-v1, 2013.
2. Arain, M., Quetschke, V., Gleason, J., Williams, L., Rakhmanov, M., Lee, J., Cruz, R., Mueller, G., Tanner, D., Reitze, D., Adaptive beam shaping by controlled thermal lensing in optical elements, Optical Society of America, United States of America, 2007.
3. Hello, P., Vinet, J., Analytical models of thermal aberrations in massive mirrors heated by high power laser beams, Université Paris-Sud, France, 1990.