Post-O5 Thermal Modeling A# TCS requirements

G2300624

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A# realistic limits: 1000kW and 4% MM SQZ Loss

Realistic limit of configurations explored so far

We're yet to find a robust TCS solution that supports ASharp target performance

Better with Super-TCS, requiring significant improvements in sensing & actuation

A# performance estimates (Preliminary)

Coating Absorption	**0.5ppm**	**1ppm**	**1.5ppm**
SQZ Loss	~4%	7%	7.2%
Arm Power	~1000kW	680kW	450kW

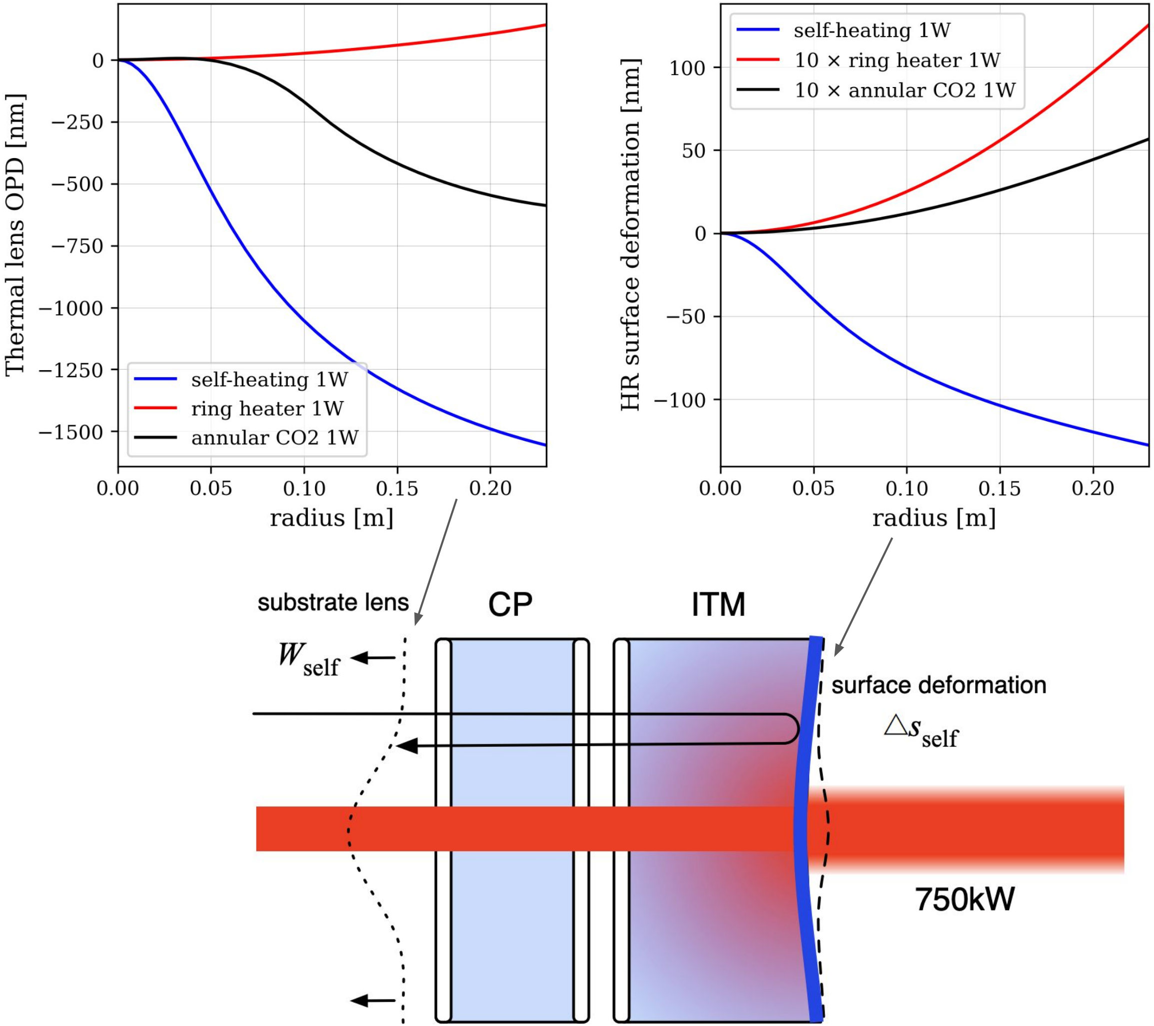
85% TCS correction (6.7x reduction in distortion)
200W of input laser power

Thermal Model

Steady state finite element models for thermo-optic deformations made

Test mass optics assumptions:

- Test mass scaled up from A+ → A# proportionally to meet 100 kg
- Compensation plate (CP) diameter scaled up to match test mass, same thickness & separation distance
- 170 mm radius aperture is assumed (no coating outside)
- 2D-axisymmetric thermal equilibrium optical profile used

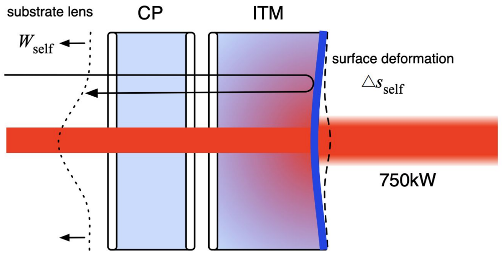


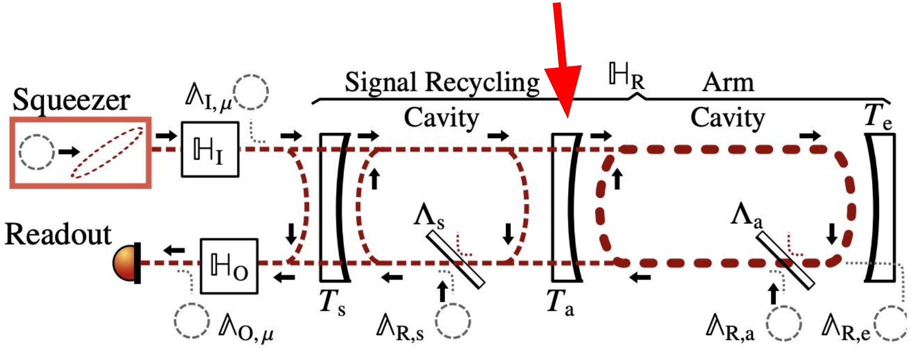
Thermal + Optical model

Full interferometer model is hard to interpret so we start the study with looking at the **PRC+ARM** and **SRC+ARM** separately and ask

How do we optimise TCS for:

- Maximum power buildups (CARM)
  - Power recycling gain (PRG)
  - Arm cavity gain
- Minimise squeezing losses (DARM)
  - Reduce higher order mode losses
  - Mis-rotation of the squeezed state





$$\theta(\Omega) = (\arg(\mathfrak{h}(+\Omega)) + \arg(\mathfrak{h}(-\Omega)))/2, \qquad (52)$$

$$\eta(\Omega) = (|\mathfrak{h}(+\Omega)|^2 + |\mathfrak{h}(-\Omega)|^2)/2, \qquad (53)$$

$$\Xi(\Omega) = (|\mathfrak{h}(+\Omega)| - |\mathfrak{h}(-\Omega)|)^2/4\eta. \qquad (54)$$

Model the upper and lower sideband transfer functions in FINESSE/SIS to get the squeezed state response

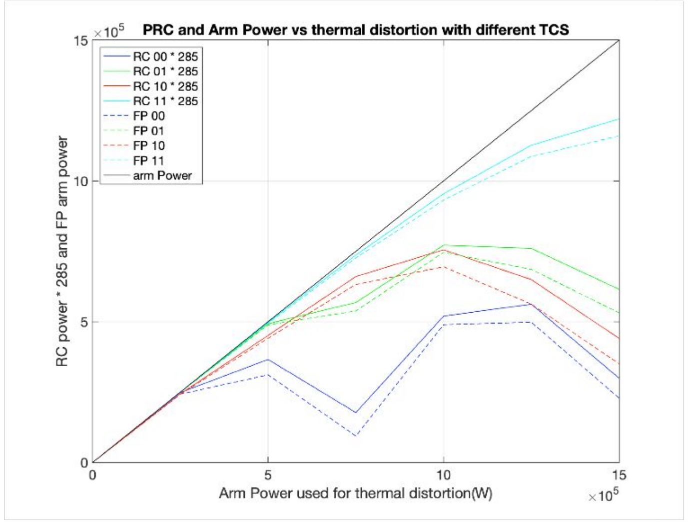
See paper *LIGO's quantum response to squeezed states*

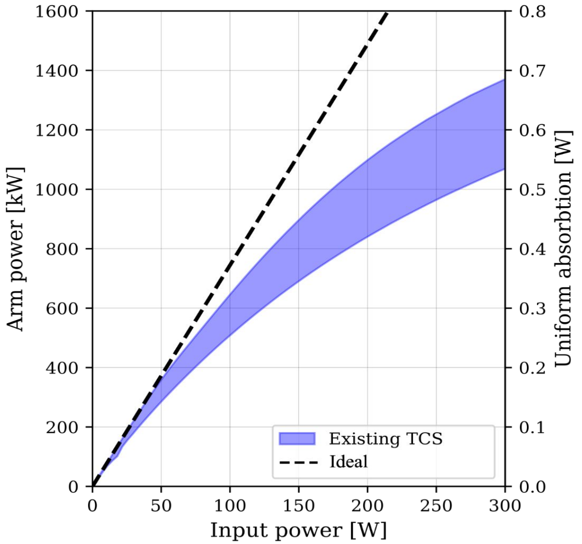
Initial findings: Power build-up

Optimising for maximum power buildup and minimised squeezing losses is not always the same TCS settings.

- **Power buildups sensitive to spot-size weighted thermal-lens and surface deformations in PRC+ARM**
- But, squeezing losses sensitive to full aperture distortions due to higher order modes resonating in the SRC

Overall we need to reduce wavefront distortion across the full aperture! A challenging TCS problem…





Initial findings: SRC loss

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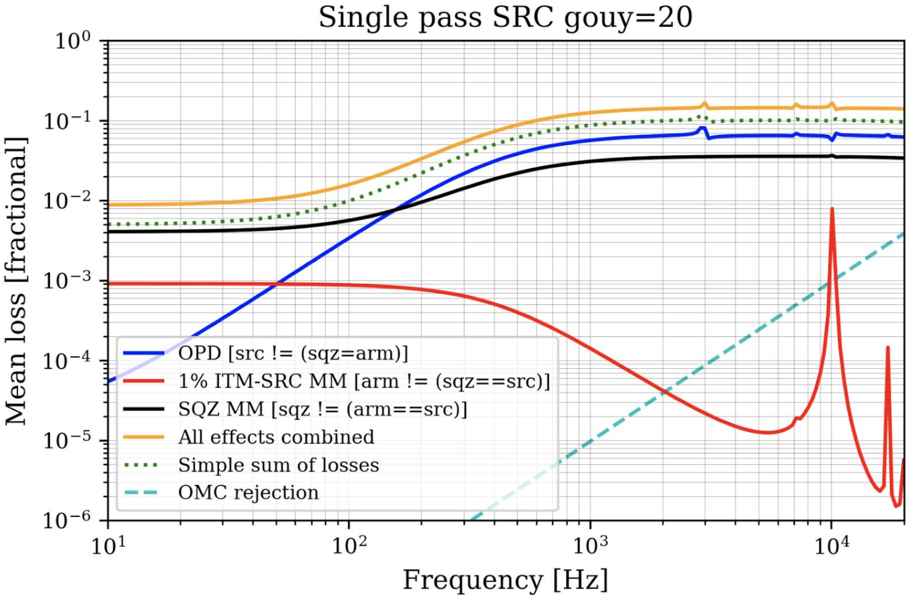

SRC-ARM mismatch (coupling to HOM2) is not a big issue

Higher order mode substrate scatter has the biggest effect on squeezing at high frequencies

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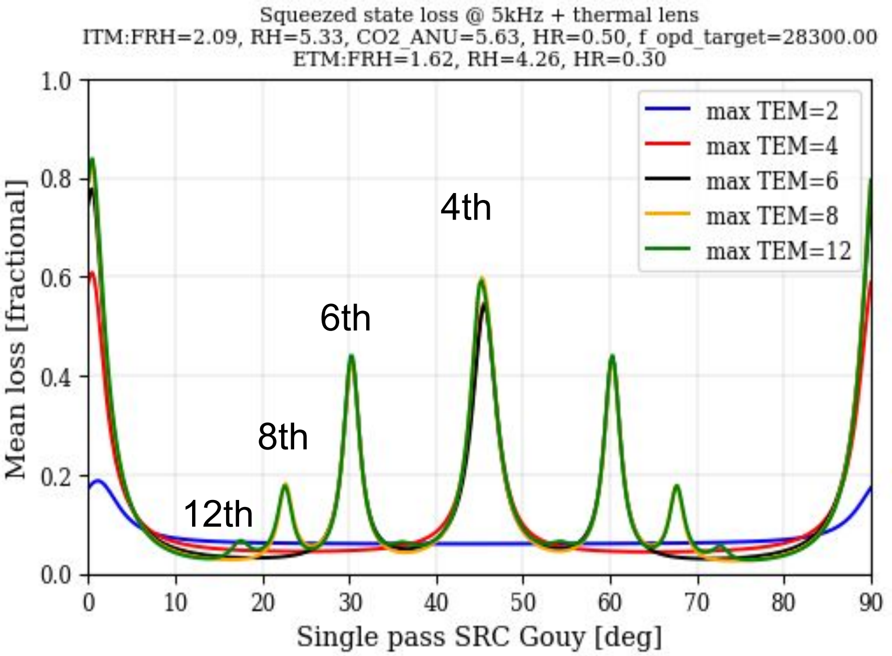

SRC gouy phase determines which HOM resonates and give high frequency losses

aLIGO SRC is around 20 degrees, which can change with thermal lensing state

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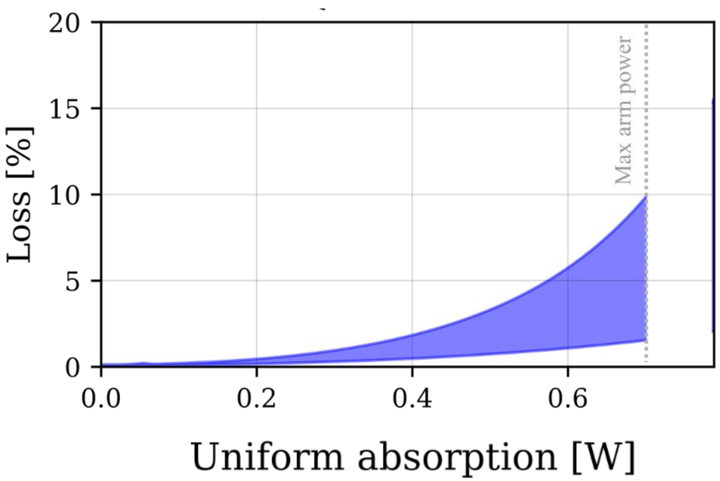

- **SQZ loss** at 500 Hz can range between 2% - 10% depending initial cold state static lens
- **Misrotation**: maximum ~ 1.5 degree @ 500 Hz
- **Dephasing**: 0.04 mrad @ 500 Hz

→ small misrotation and dephasing

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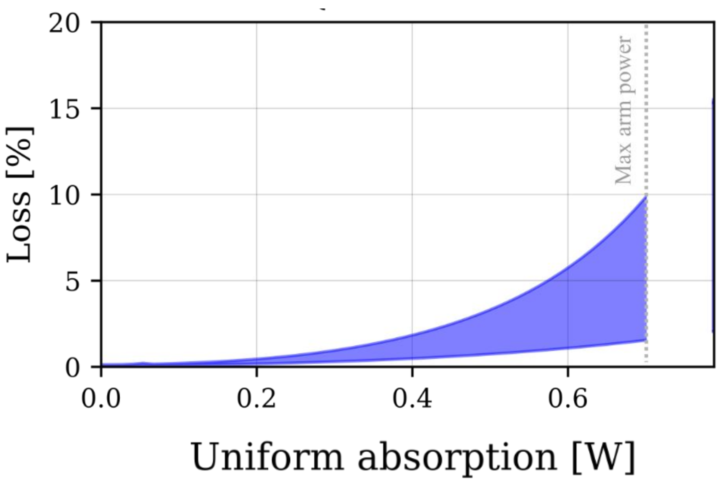

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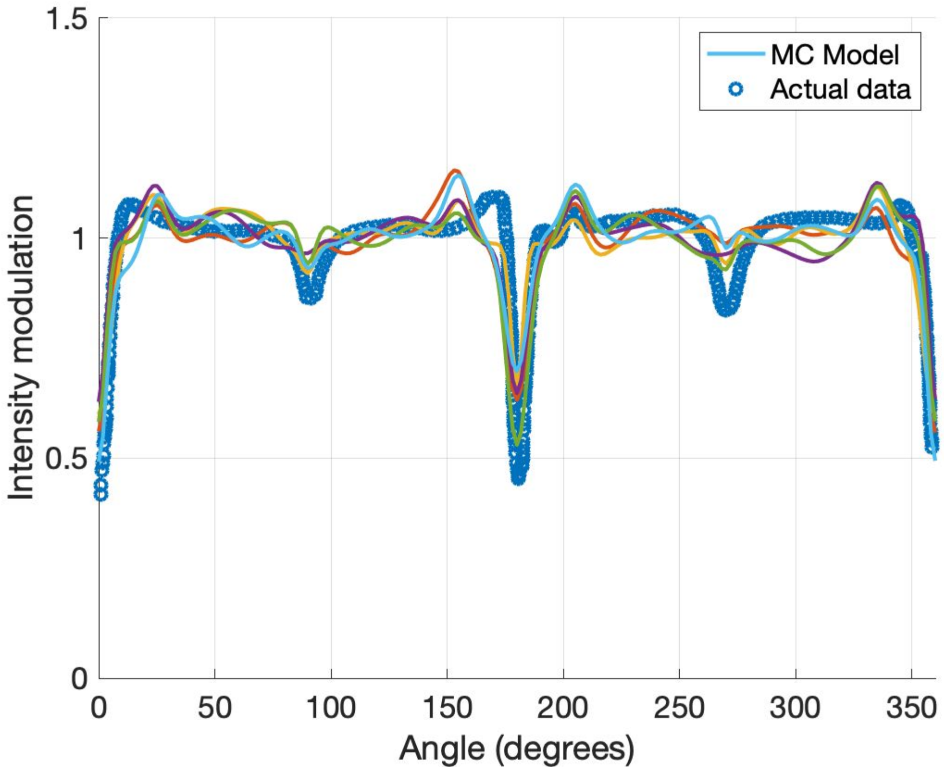
Adding TCS variations (based upon real systems)

Ring Heater axial variations

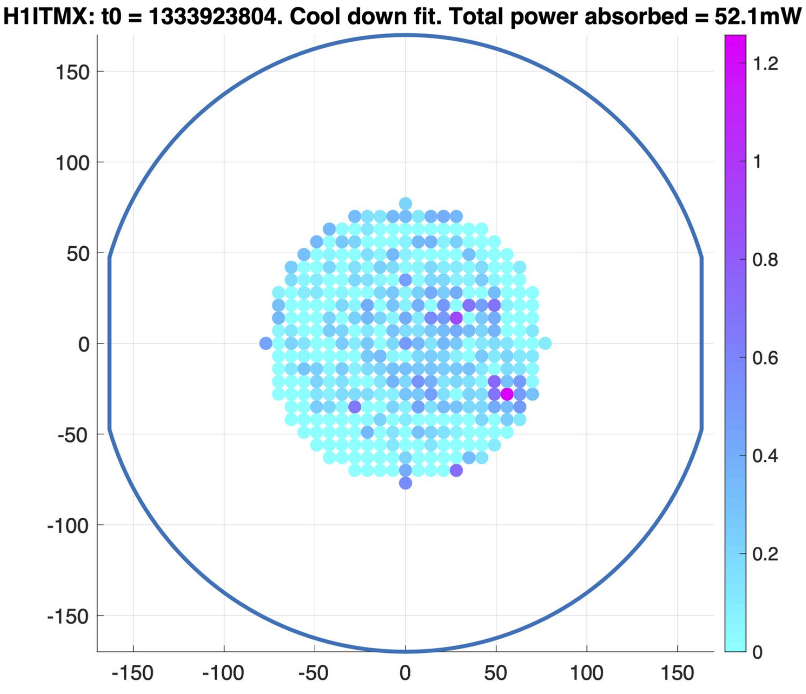


CO_2 Laser (approximations)

Parameter	Variation
Alignment to mask*	± 3mm
Beam size	± 5%
Magnification	± 5%
Alignment to CP	± 4mm

* Referenced to full-size heating beam at CP

Adding TCS variations (based upon real systems)

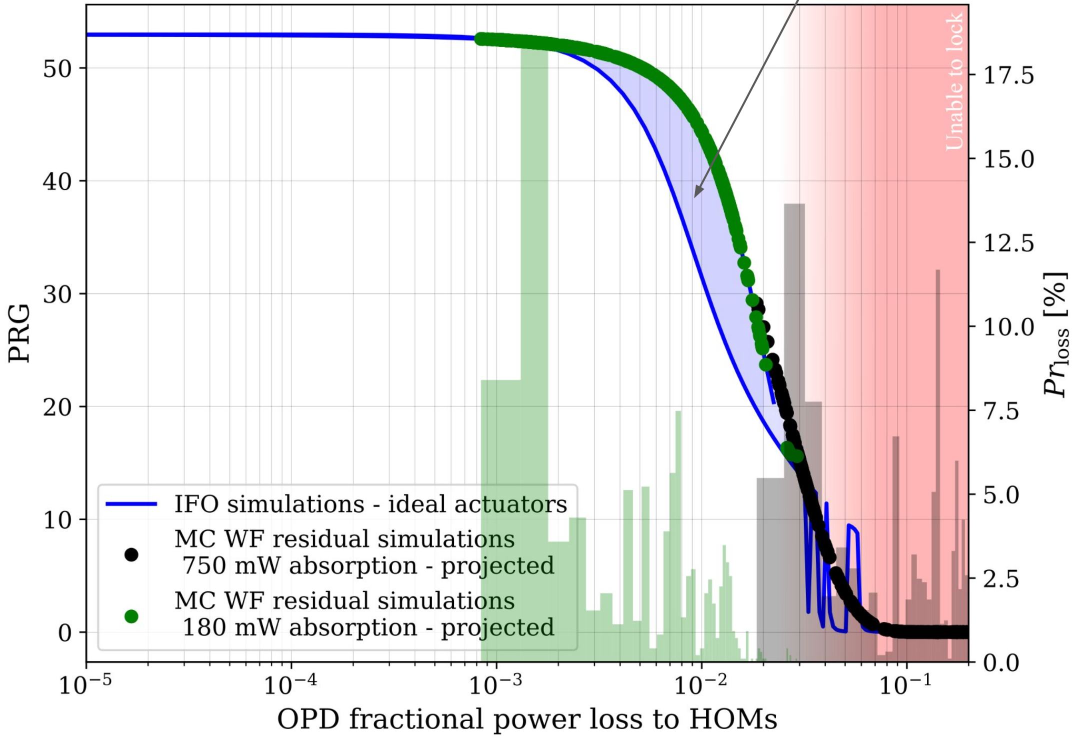


- Non-uniformity observed in recorded in Hartmann wavefront sensor
  - Non-uniform absorption on larger spatial wavelength scale (> 2 cm)
  - Uncertainty in sensor
- **MC data set include variation in absorption point-to-point:**
  - 68%: 0.5 ± 0.05 ppm
  - 27%: 0.5 ± 0.15 ppm
  - 5% : 0.5 ± 0.5 ppm

Preliminary results: Monte Carlo simulation

Variations dependent on TCS configurations , i.e. residual spatial structure

- For each optimised map: compute fractional power loss to HOMs
- Plot PRG as a function fractional power loss
- Compute optimised maps and their fractional power loss from Monte-Carlo dataset
- **Project MC data to the trend obtained from IFO simulation**

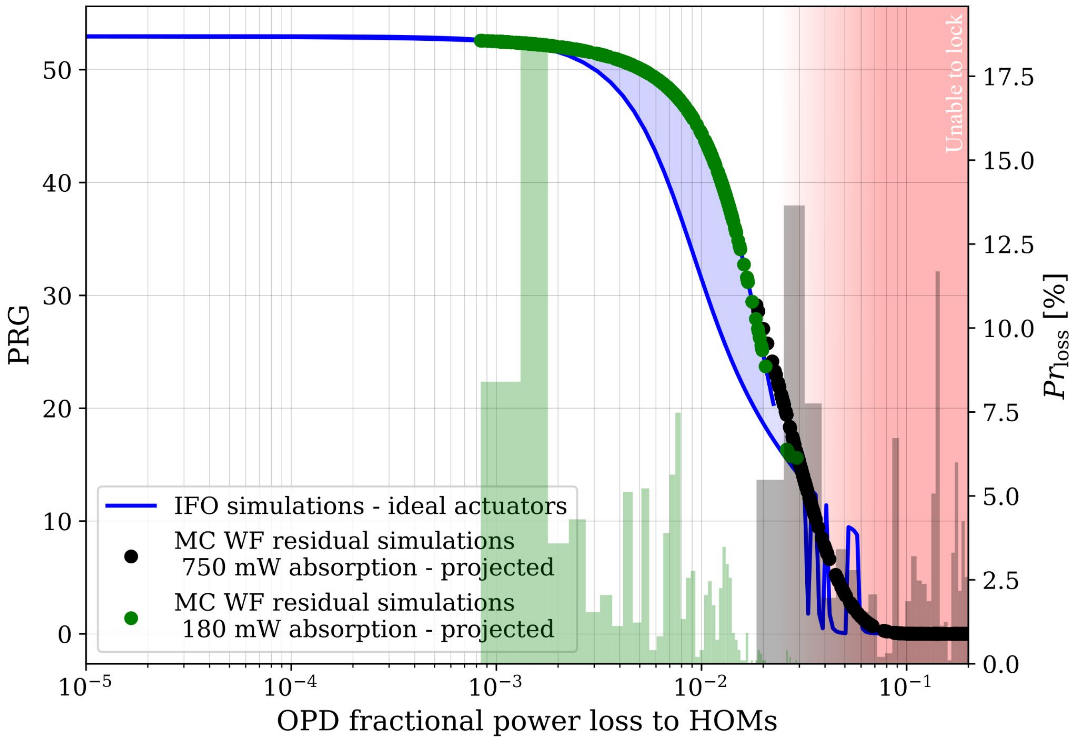


Preliminary results: Monte Carlo simulation

- At 750 mW HR absorption distortion, HOM loss from OPD is most likely 2-5%

  → **PRG drops to 5 - 10**

- **Couldn't find operating point to lock in many cases**



Preliminary results: Monte Carlo simulation

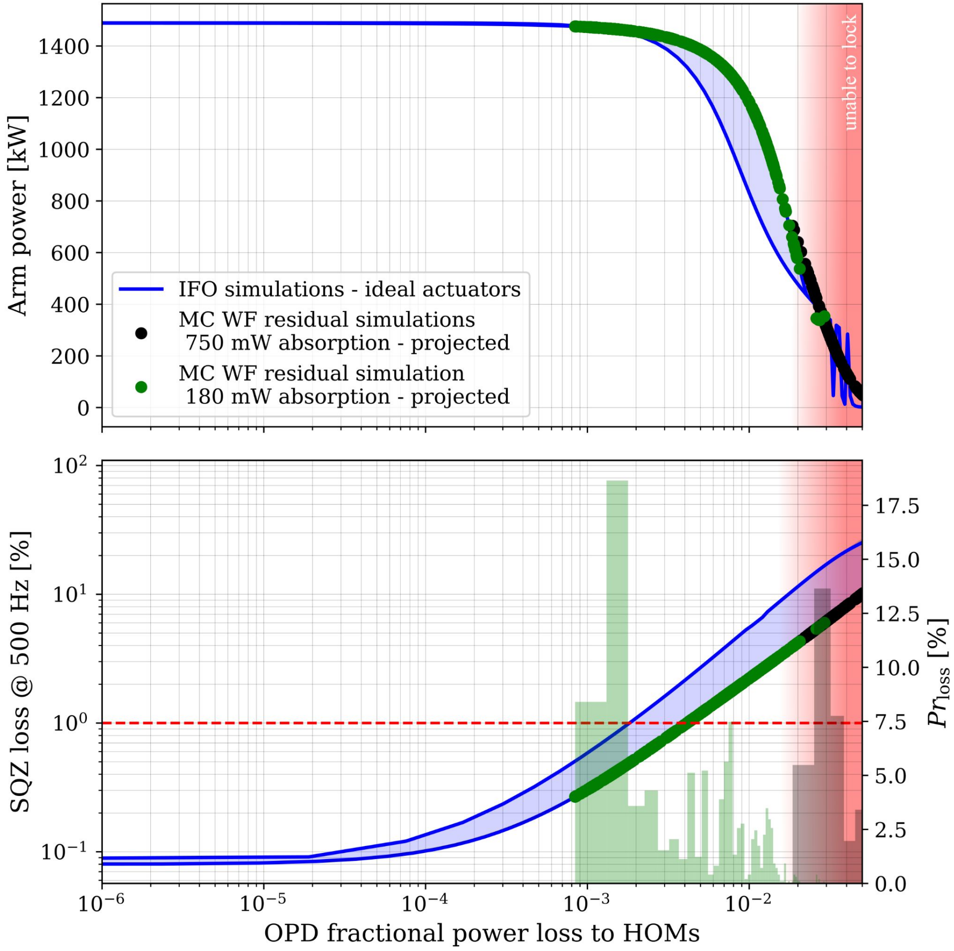
At 750 mW absorption:

- **SQZ loss @ 500 Hz > 5% in all cases**
- No self-consistent solution that results in 750 mW absorption

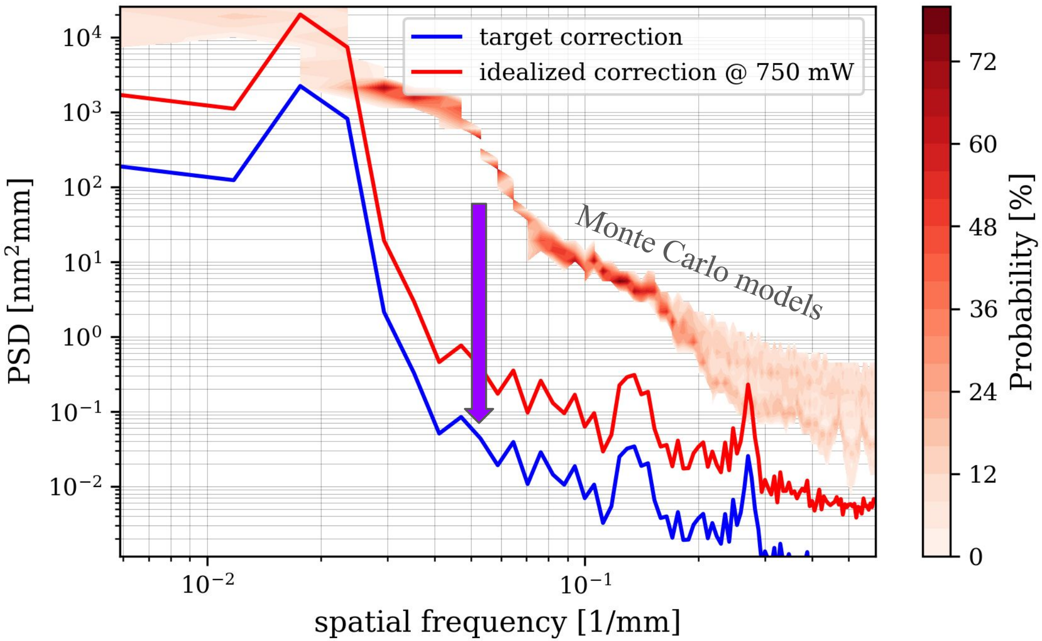
Require a self-consistent solution where the arm power achieved can generate the right residual lens that allows such arm power (sufficient PRG and arm gain)

*** Preliminary results** (for 200 W injection)

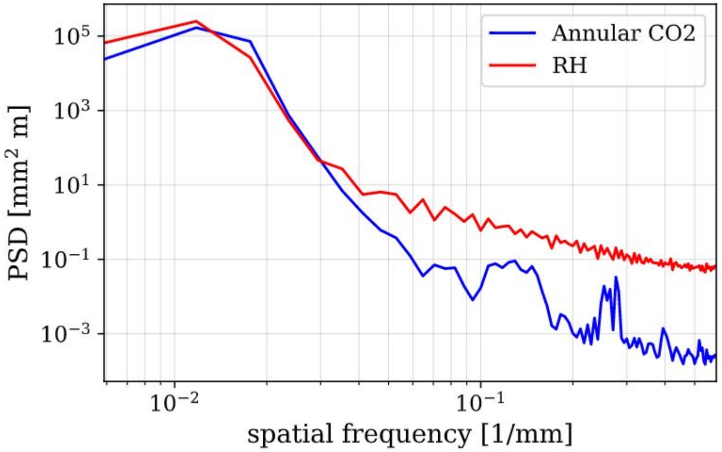
Absorption	**0.5ppm**	**1ppm**	**1.5ppm**
SQZ Loss	~4%	7%	7.2%
Arm Power	~1000kW	680kW	450kW



What is our cancellation capability?



- Errors in actuators result in excess of distortion in spatial wavelength band between 5 mm - 3 cm
- Light scattered from structures of this scale remains inside optical cavity and interact with main IFO beam → complicated and hard to predict behaviour
- **No existing actuator designed to target this band.**



Continued R&D

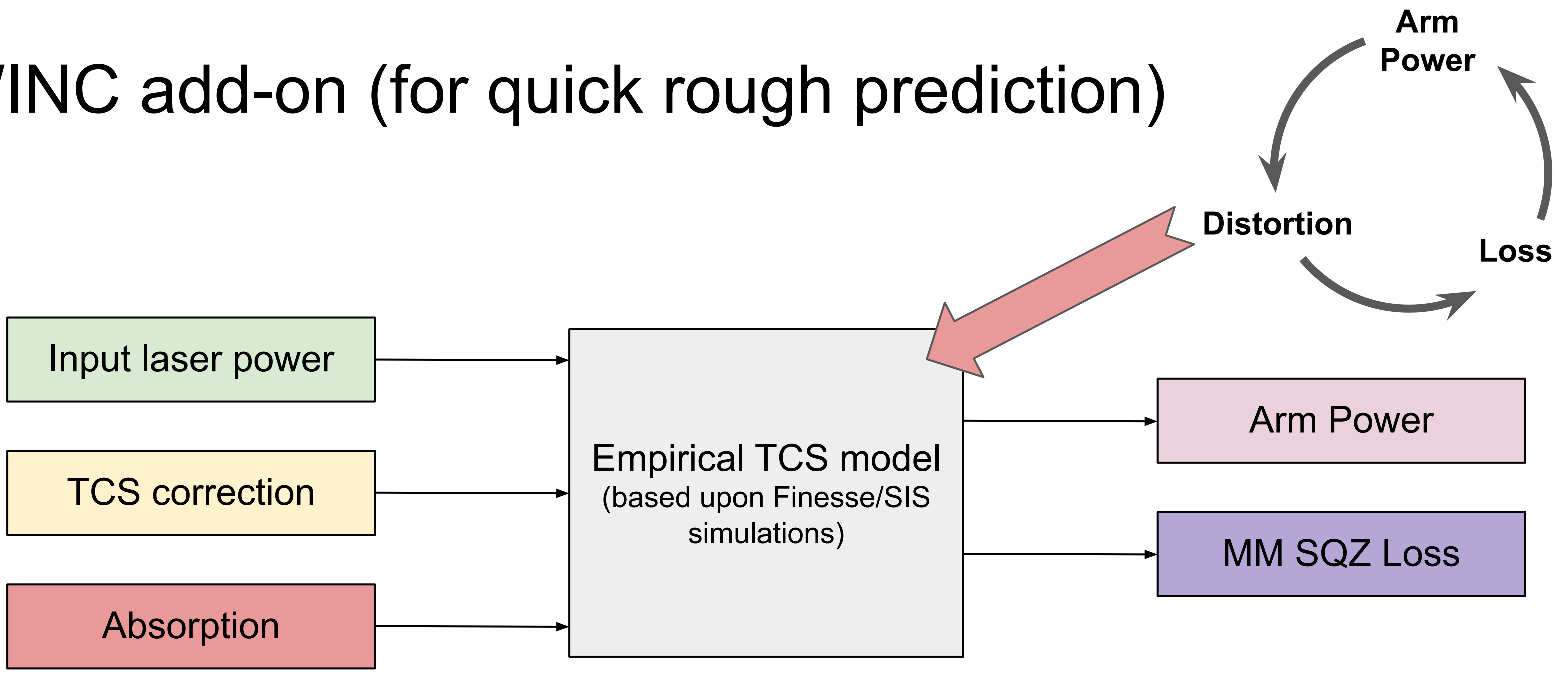
- **MC models:**
  - Working with the sites for better representation of errors in actuators/ sensors
  - Run SIS/ Finesse with MC dataset (rather than just projecting)
- **Full IFO models:**
  - Explore differential effects
  - Noise coupling (intensity noise/ frequency noise)
  - Effects on control signal
- **Transient dynamics:** varying thermal state of test masses → IFO beam changes dynamically → change thermal state
  - Incorporate FEA into SIS/ Finesse to solve simultaneously
  - Simulate and compare to measured transient response (power monitoring/ wavefront sensing channels)
- **O4 model:**
  - Focus back on O4 IFO model to verify simulation
- **A# TCS requirement on sensing + actuating:**
  - Set requirements on errors of TCS actuators
  - Optimise new actuators (front surface heaters/ CO_2 upgrade) for full aperture correction
  - Developing correction capability for medium spatial wavelength (1-7 cm)

Key take-away messages

- **Existing TCS is not ready for correction at 1.5 MW, will need a factor of 20-30 of distortion suppression**
  - Single-pass OPD loss $\lesssim$ 0.2% for both 1.5 MW arm power + 1% SQZ loss at 500 Hz
- **We're yet to find a robust TCS solution that supports A# target performance**
- **Significant improvement in sensing is required to reliably correction out to at least twice IFO beam size**
- **Actuation at medium spatial wavelength is required to suppress OPD loss to required level**

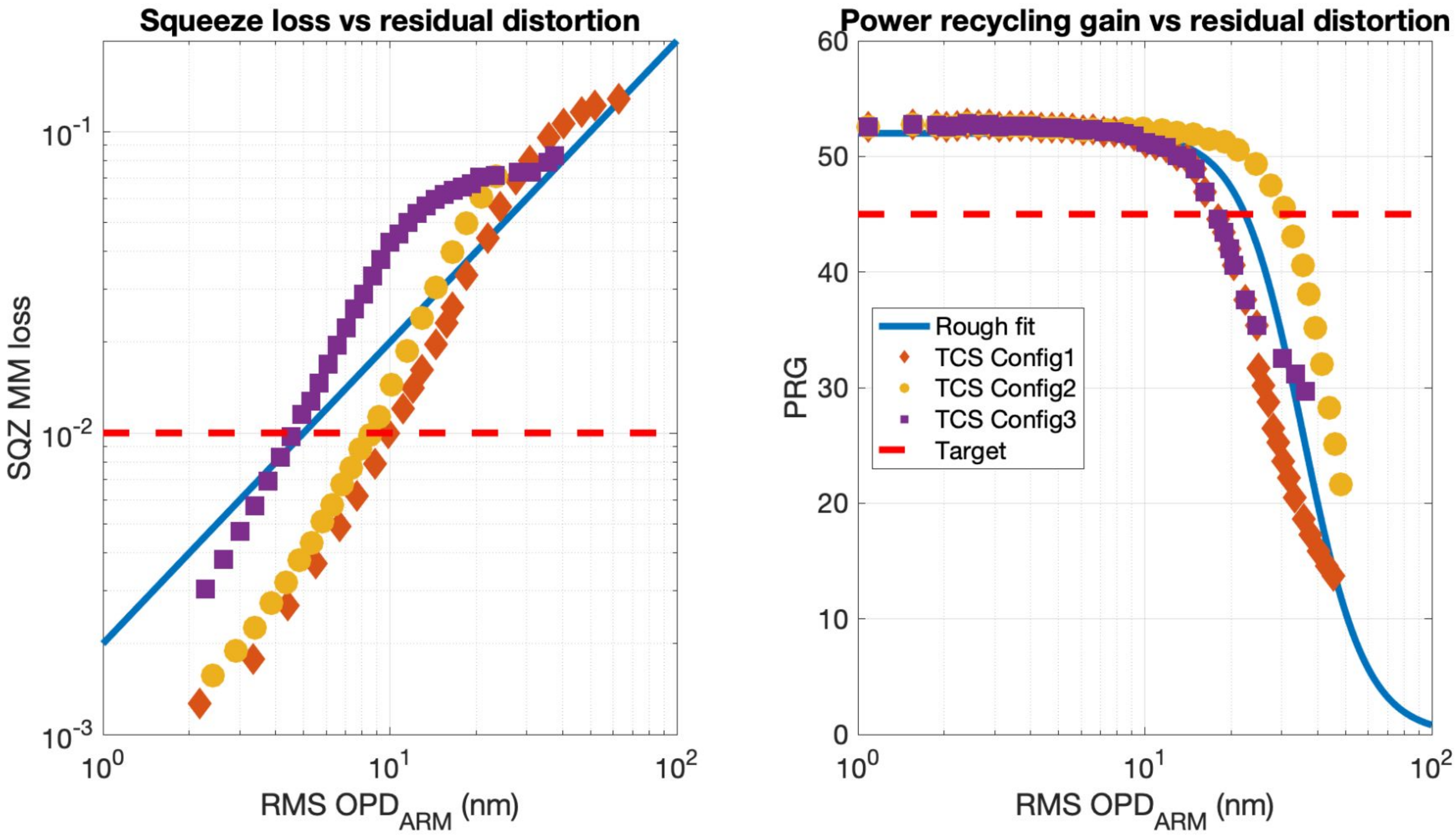
SUPPLEMENT SLIDES

GWINC add-on (for quick rough prediction)



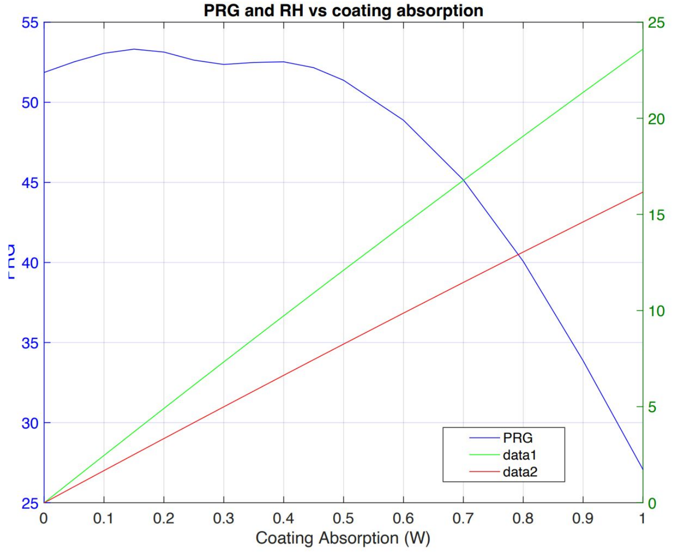
- Code roughly predicts self-consistent IFO performance
- (based upon simulation data).
- Incorporates real simulation data without GWINC having to run full Finesse/SIS

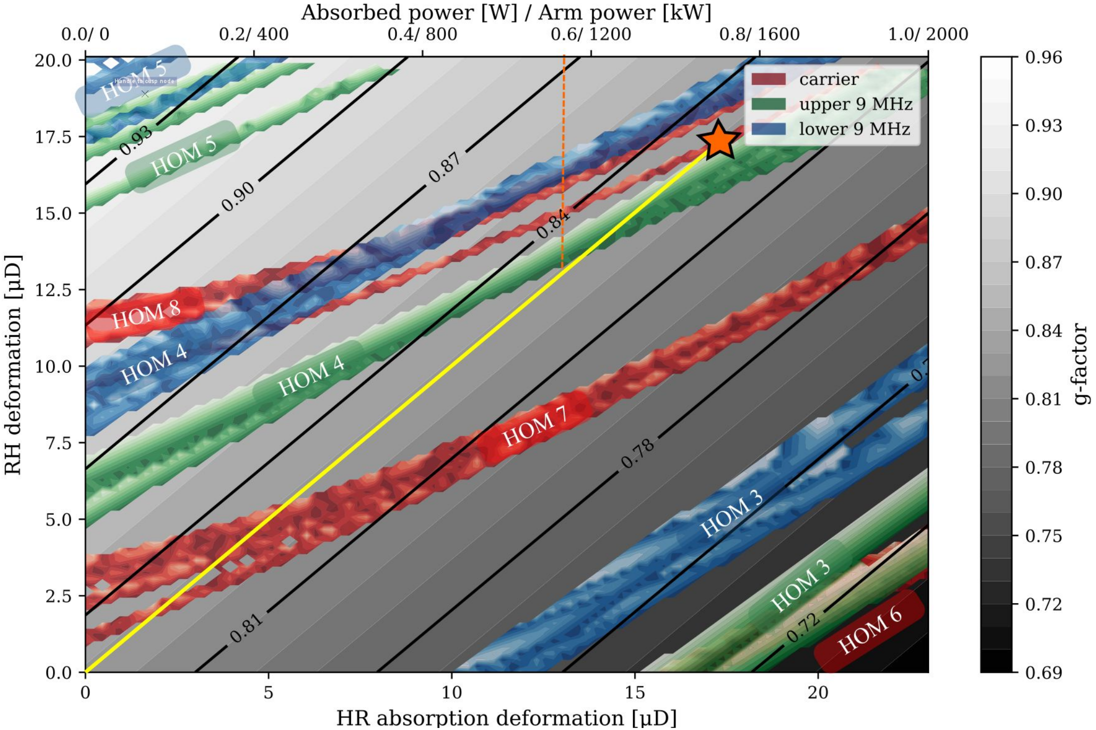
GWINC add-on (empirical data)



D. Brown (Adelaide), H-T, Cao, J. Richardson, L. McCuller, C. Wipf, H. Yamamoto, A. Brooks (CIT): T2200310 (soon)

Perfectly removal of thermal lens with CO2





Effects of changing larger aperture