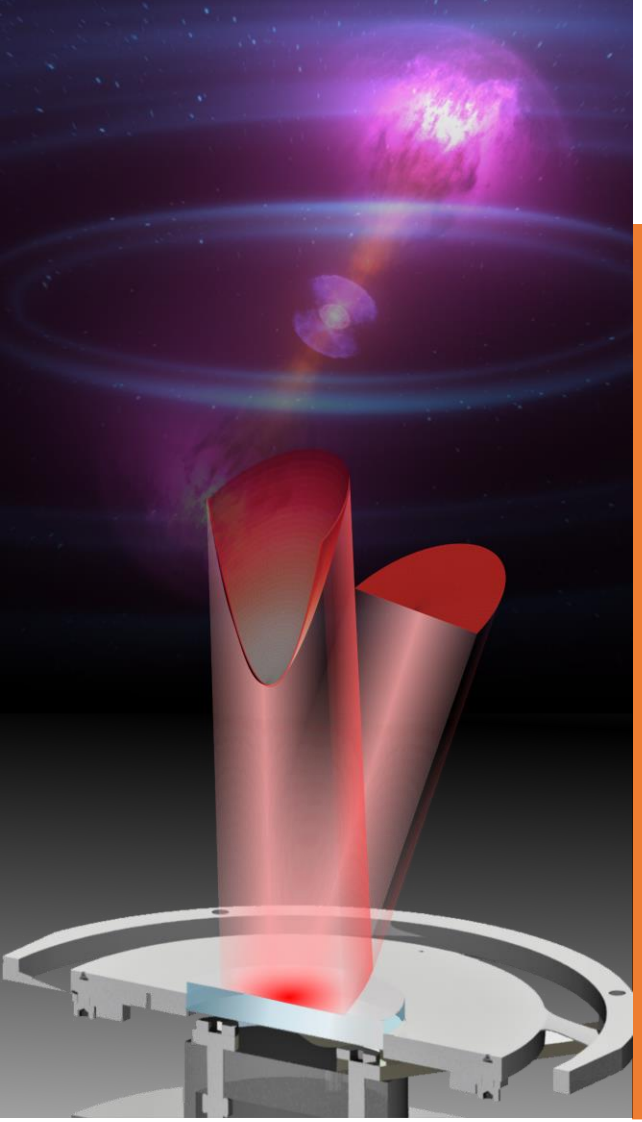

A Compression Fit Mirror for Active Wavefront Control

G2001570

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1 Motivation: Adaptive Optics for GW Astronomy

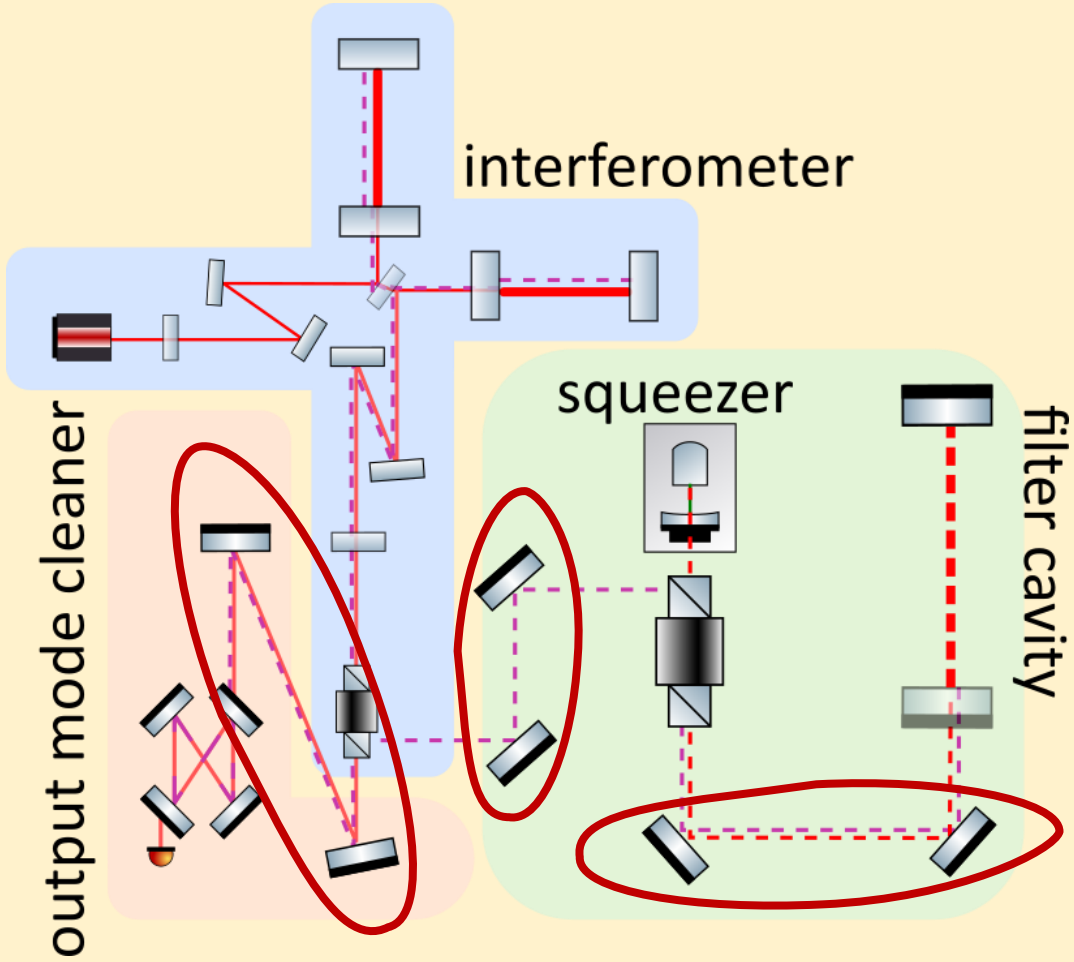


Fig.1. O4 simplified configuration and location of mode-matching

(See Varun talk @ 16:20 BST for more details)

2020-2021 Upgrade:

- Squeezer mode matching:
  - squeezer → filter cavity
  - filter cavity → interferometer
- Output mode matching:
  - interferometer → output mode cleaner

Requirements:[4]

- High dynamic range. *Defocus*† range ≥ 200 mD
- Low aberration, high-order mode scattering loss < 0.4%
- High spatial frequency actuation not necessary
- Ultra high vacuum compatible
- Easy integration into suspension system
- Low defocus noise: $\leq 1\ nD/\sqrt{Hz}$

→ **S**uspended **A**ctive **M**atching **S**tages project

† Defocus $S := {}^{2}/_{ROC}$, ROC is mirror's radius of curvature

1 Motivation: OMC-IFO MM needs high actuation range

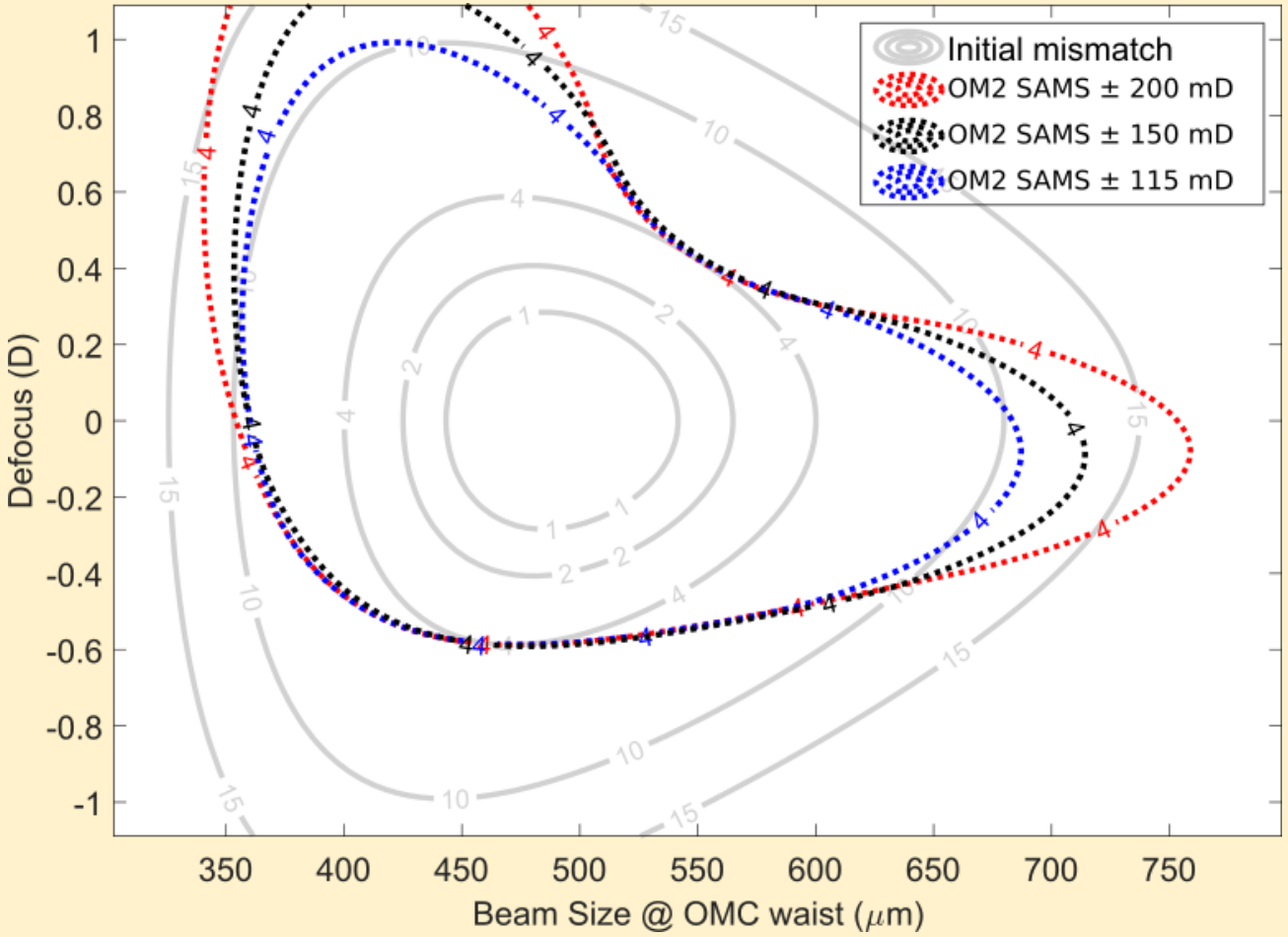


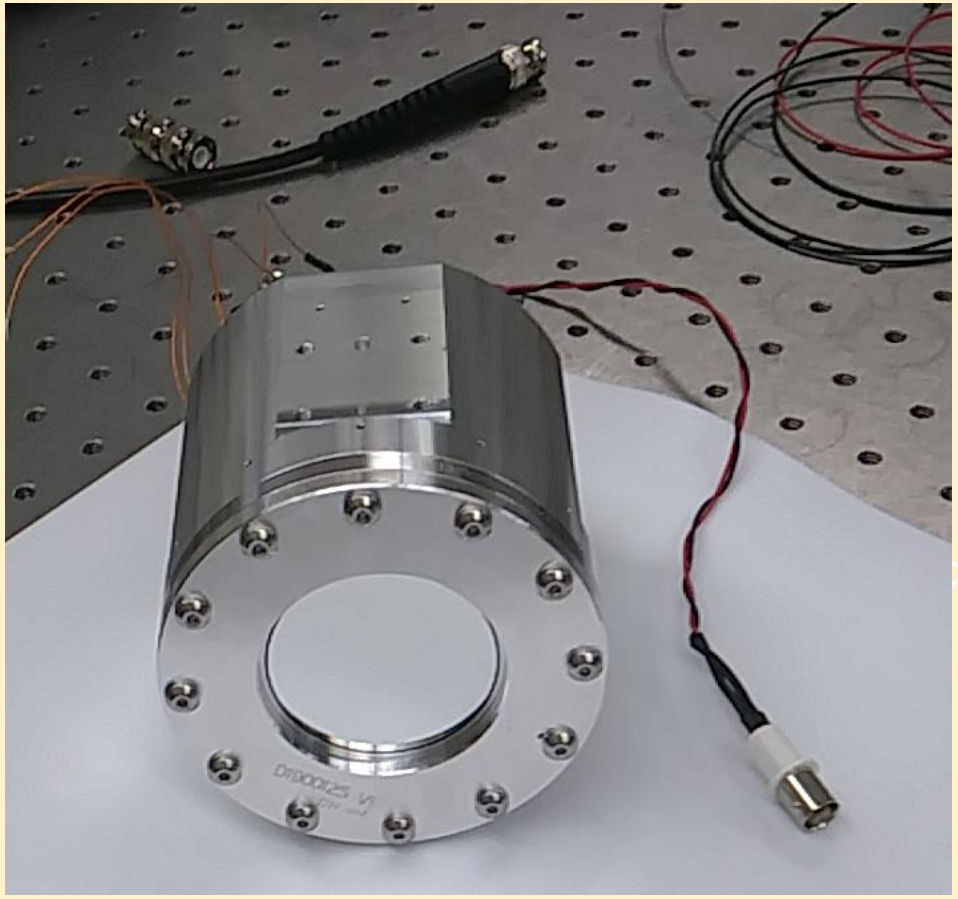
Fig.2. Region of initial mismatch able to be corrected up 96% mode-matching with OM2 SAMS

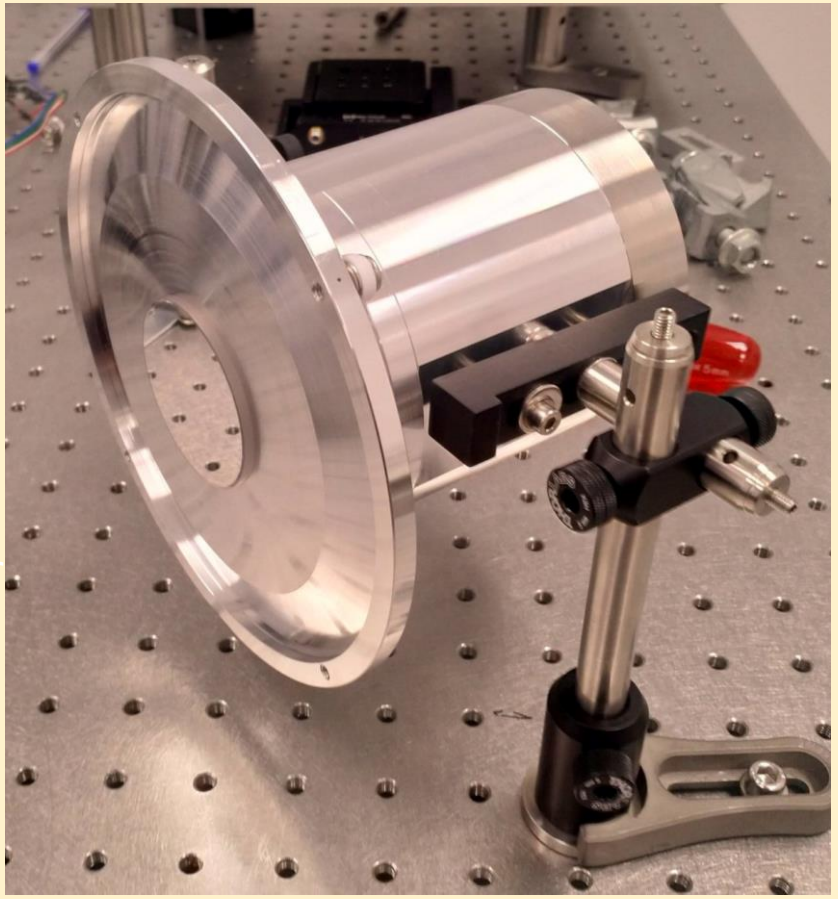
- High actuation range required for IFO→OMC mode matching.
- Current design actuation range (± 155 mD) has 32.5% success rate in correcting 9% mismatch to 4% (and 0% to 2%)

1 Motivation: The Need for a New Deformable Mirror

	Types	Drawbacks
Commercially Available	• Stacked array [5] • Unimorph/ bimorph PZT [6] • MEMS [7]	• Challenging for suspension integration • Trade-off between surface quality and actuation range • Vacuum incompatible • High-cost
GW Adaptive Optics	**Transmissive style:** • Single element Rear heater [8] • Resistor array [9] • Ring heater [10]	• Low actuation range • Excess of scattering/absorption loss due to more optical surfaces
	Front reflective style: • Thermal bi-morph mirror [11]	• Stress limited due to epoxy bonding • High uncertainty in epoxy performance • Tensile stress limited in fused-silica

1 Suspended Active Matching Stages (SAMS)





Piezo deformable mirror (PDM):

- Piezo driven
- Higher bandwidth, lower actuation range

(Look out for Varun's talk at 16.20 BST)

Compression-fit mirror (CFM):

- Thermal driven
- Lower bandwidth, higher actuation range

2 Concept: The Compression-fit Mirror

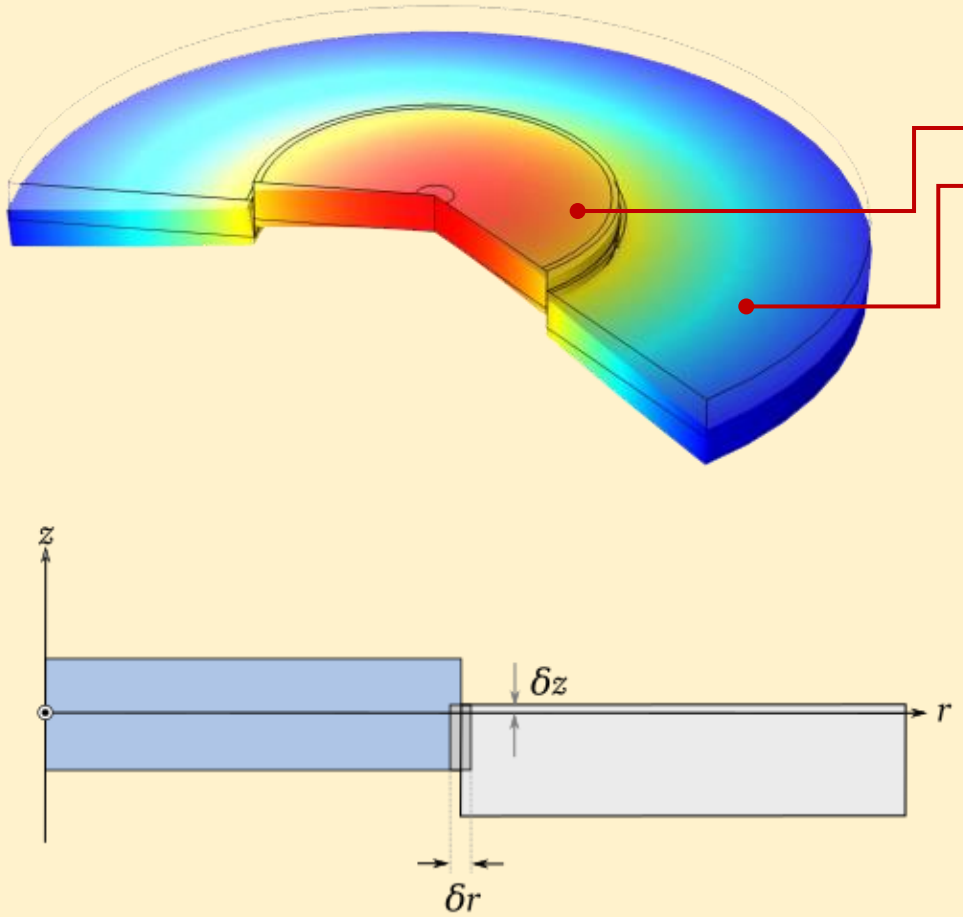


Fig.3. Schematics of a simple compression-fit mirror

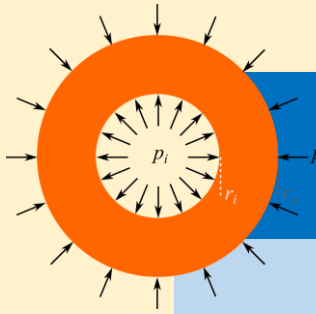
A basic compression-fit mirror consists of:

- **A fused-silica mirror**
- **An aluminium actuating ring**

- Silica coefficient of thermal expansion (CTE) << aluminium CTE
- Mirror is captured inside an alumininum ring, at elevated temperature by shrink-fitting
- Axial offset between ring and mirror + interfacial stress induces bending moment deforming mirror
- Re-heating the assembly changes radial interference δr

→ tuning mirror curvature

2 Concept: A Simple Analytical Model



Thick-wall Cylinder Theory

Interfacial stress p:

$$p = \frac{\delta r}{\frac{a}{E_{Al}}\left(\frac{r_o^2 + a^2}{r_o^2 - a^2} + \nu_{Al}\right) + \frac{a}{E_{silica}}(1 - \nu_{silica})}$$

- ν: Poisson's ratio
- E: Young's modulus
- r_o: Ring outer radius
- a: Nominal mirror radius
- t_m: mirror thickness



Plate Theory

Moment: $M = \int p\, z dz$

Curvature: $\kappa = \frac{1}{R_m} = \frac{M}{D(1-\nu)}$

$D \equiv$ Flexural rigidity

$$S = 2\kappa = \frac{24(1 - \nu_{silica})\delta r}{a\left[\frac{E_1}{E_2}\left(\frac{r_o^2 + a^2}{r_o^2 - a^2} + \nu_{Al}\right) + 1 - \nu_{silica}\right]}\left(\frac{\delta z^2}{t_m^3} - \frac{1}{4t_m}\right)$$

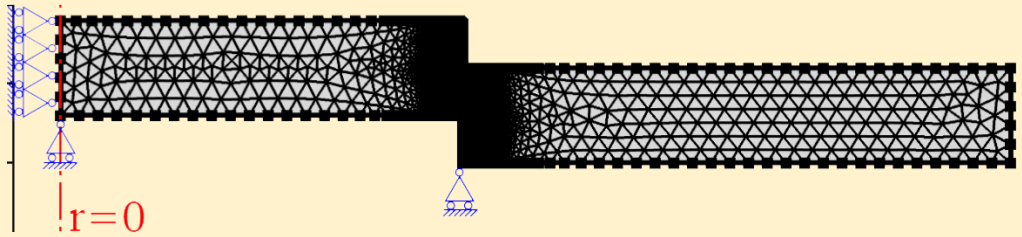
- **increases** linearly with **increasing** interference
- **decreases** quadratically with axial offset from barrel centre, **maximum at 0**
- **inversely proportional** to mirror thickness at $\delta z = 0$
- **inversely proportional** to mirror diameter when $r_o \gg a$
- **increases** with **increasing** outer diameter but **plateaus** as $r_o \gg a$

From CTE relation:

$\delta r \approx a\Delta\alpha\Delta T$ for $\alpha_{Al}\Delta T \ll 1$

- Defocus **changes linearly** with temperature

3 Modelling: A Finite Element Model (FEM)



Component	Parameters	Value
Mirror	radius a [mm]	50.8
	thickness t_m [mm]	6.0
Actuating ring	outer radius r_o [mm]	55
	thickness t_r [mm]	6
	offset δz [mm]	0

Material	Properties	Value
Fused silica	Young's modulus [GPa]	73.6
	Poisson ratio	0.17
	CTE [1/K]	0.57e-6
Aluminium	Young's modulus [GPa]	68.9
	Poisson ratio	0.33
	CTE [1/K]	23.6e-6

COMSOL Multiphysics FEA Simulation
Coupled model: Heat transfer in solid + Solid Mechanics

Physics

- Heat transfer in solid:
  - Ambient temperature: 298 K
  - Initial temperature: 298 K
  - Stage 1 heating: Lower surface temperature = 373.15 K
  - Boundary condition: radiative heat transfer
- Solid mechanics:
  - Constrained displacements at 2 points to suppress rigid motion:
  - Contact study, friction coefficient: 0.9

Studies

2-step stationary studies

- Study 1: heating two components to 100oC
- Study 2: allowing two components to cool down and come into contact

3 Modelling: Highly Spherical Deformation

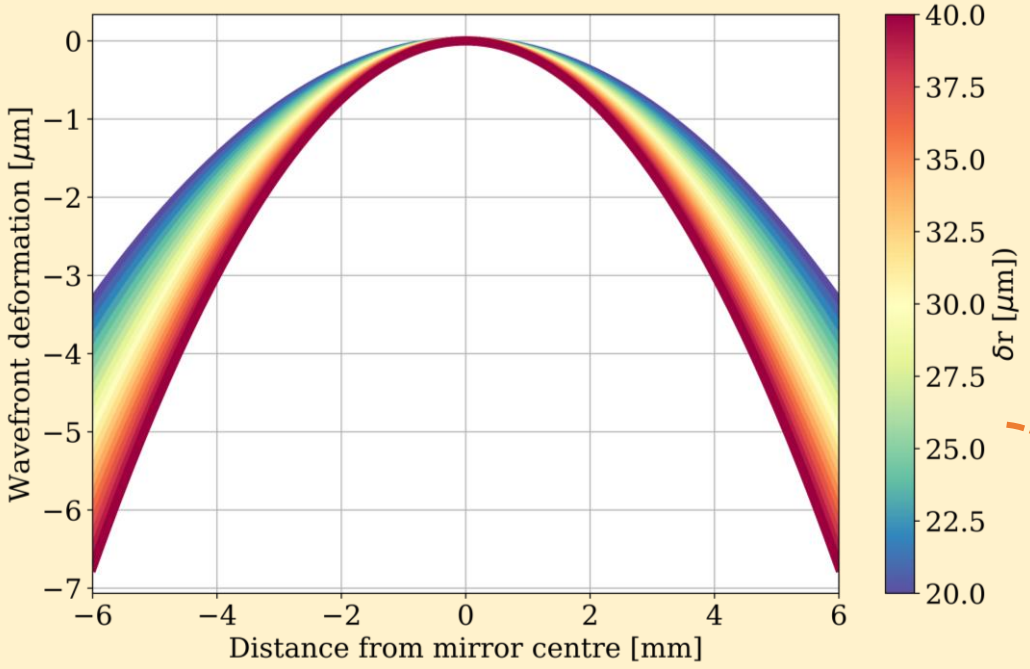
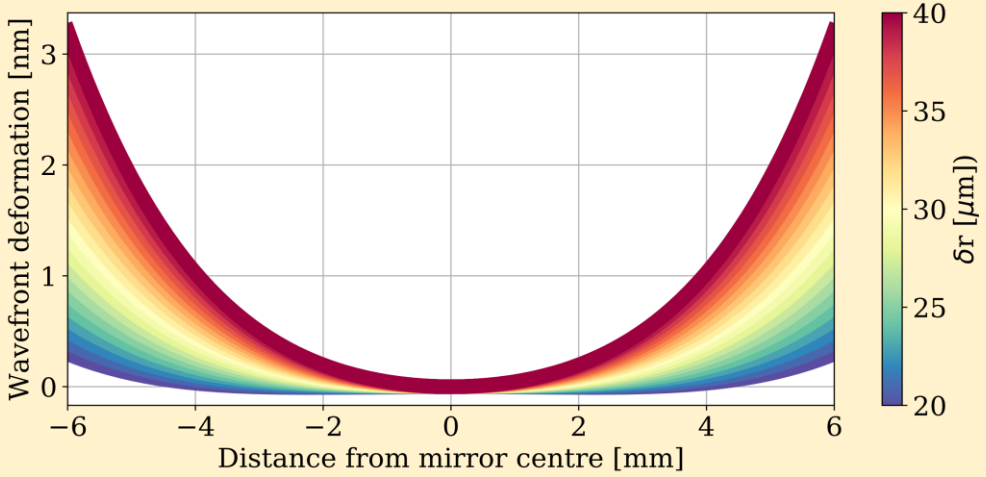


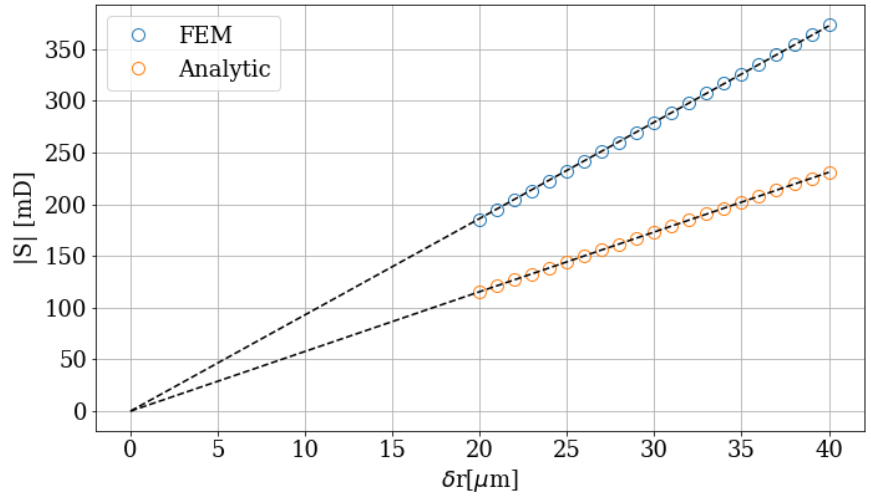
Fig.4. FEA results of mirror deformation before and after removal of defocuss

Correction factor 1/0.62

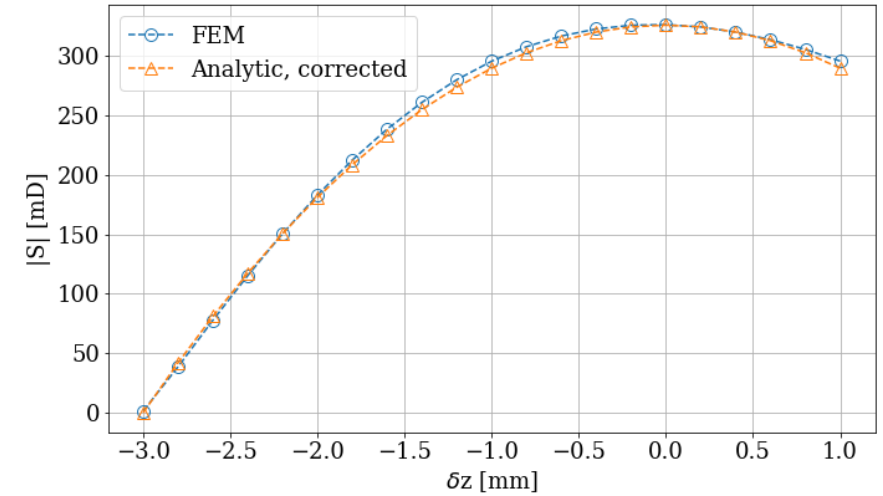


High-order aberration

δr



δz



3 Modelling: Bulk stress is well within safety limit

Aluminum

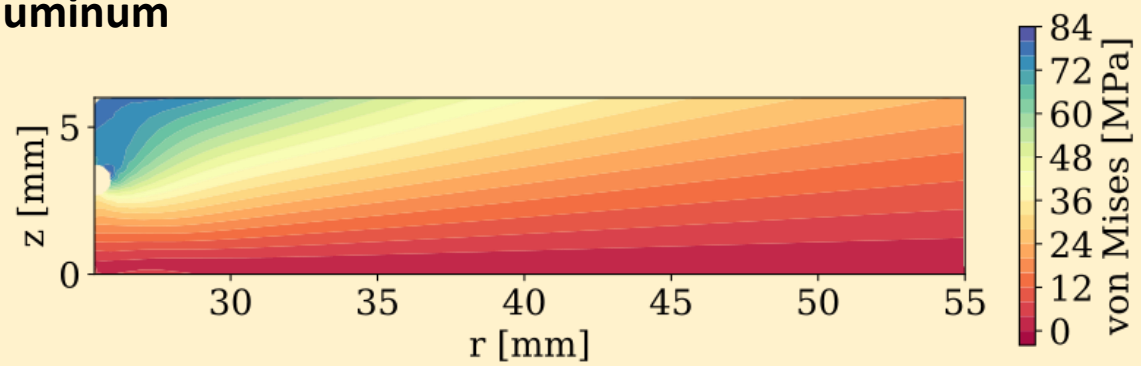


Fig. 5. FEA simulation of von Mises stress in aluminium ring

- **Yield strength** ≈ 276 MPa
- Max von Mises stress ≈ 84 MPa (front surface)
- Safety factor: 3.3

Fused-silica

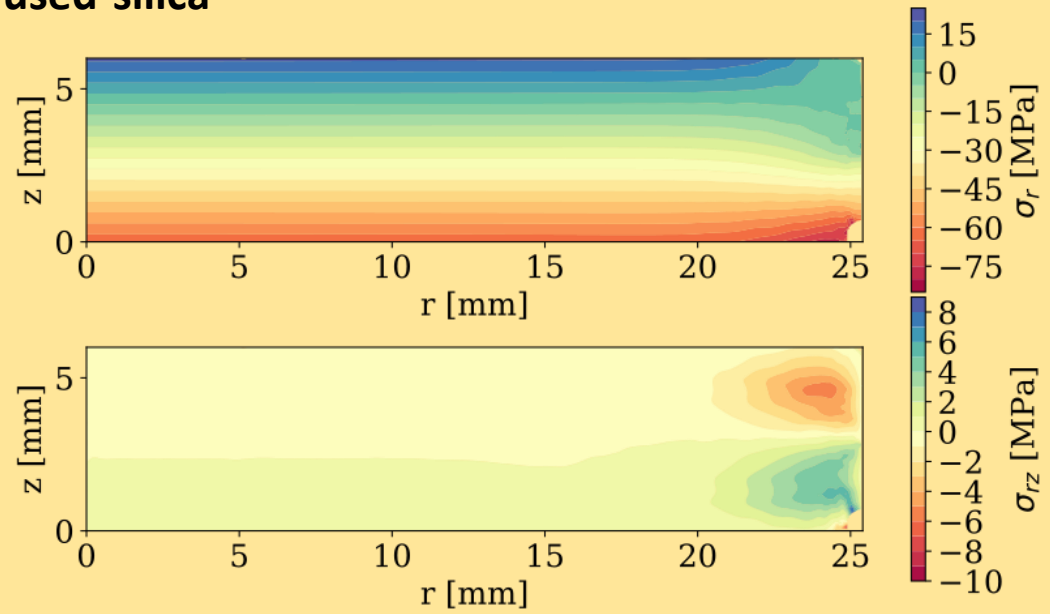


Fig. 6. FEA simulation of radial and shear stresses in fused silica mirror

- **Tensile stress:**
  - **Tensile strength** ≈ 54 MPa
  - Max **tensile stress** ≈ 21 MPa (front surface)
  - Safety factor: 2.6
- **Compressive stress:**
  - **Compressive strength** ≈ 432 MPa (Griffith's criterion)
  - Max **compressive stress** ≈ 80 MPa (rear)
  - Safety factor: 5.4
- Shear stress:
  - Shear strength ≈ 162 MPa (Griffith's criterion)
  - Max shear stress mag ≈ 10 MPa
  - Safety factor: 16.2

→ Not limited by bulk stresses

4 Prototype: A 2-inch Compression-fit Mirror

Component	Parameters	Value
Mirror	radius a [mm]	50.8
	thickness t_m [mm]	6.0
Actuating ring	outer radius r_o [mm]	55
	thickness t_r [mm]	6
	offset δz [mm]	0
	interference δr [μm]	Design: 35 Measured: 36±10
Flexures	thickness [mm]	0.3
	angle [deg]	18
	radial width	17.5
Mounting ring	thickness [mm]	6
	radial width [mm]	7.5

Table of key parameters of the compression fit mirror

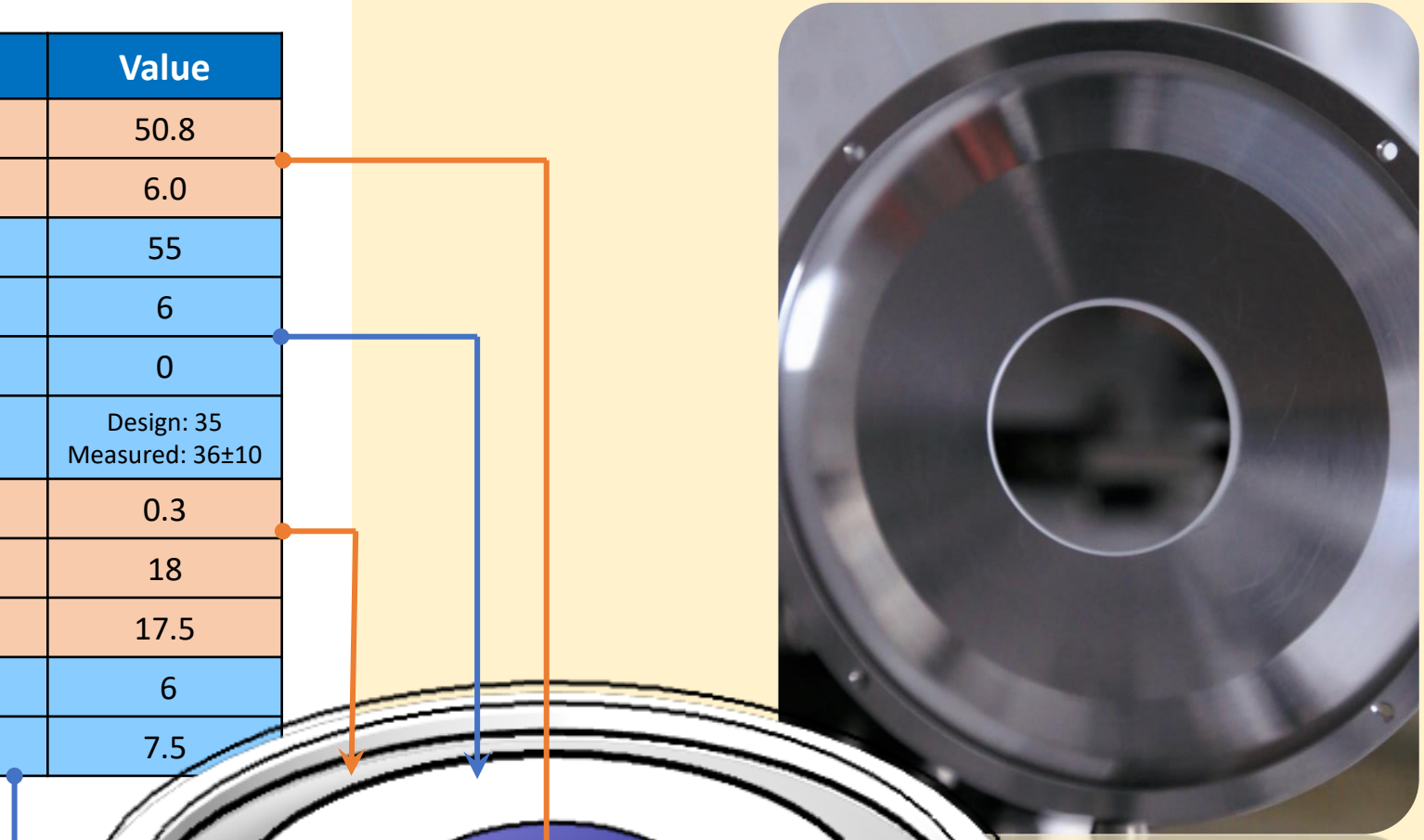


Fig. 7. Compression fit mirror prototype

5 Measurement: Highly spherical static deformation

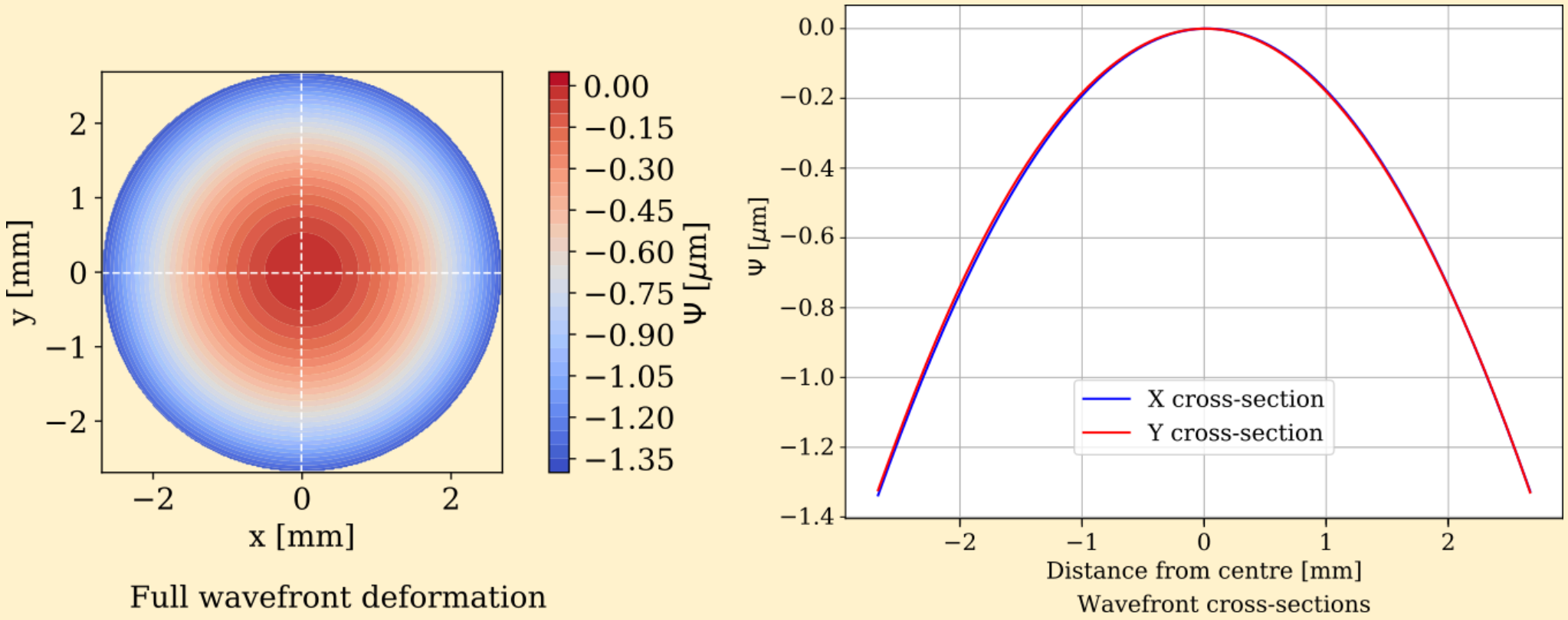
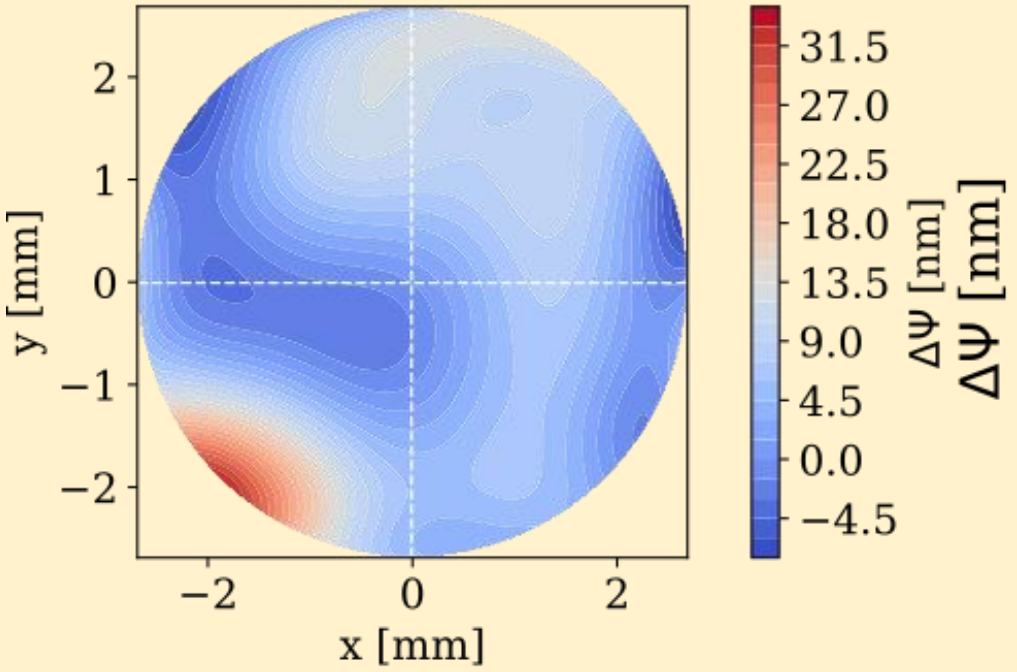


Fig.8. Wavefront deformation reflected off the compression fit mirror at ambient temperature

- Strong measured static deformation at T_{amb} = 274.5 K: -377 ± 5 mD,
- Inferred δr is 39.4 ± 0.6 µm

5 Measurement: Low higher order aberration

- Small residual astigmatism (12 mD)
- Meet current HOMS specifications (<0.4%) at target beam size (0.8 mm radius)
- Limited by reference optics



Higher order aberration

Fig.9.

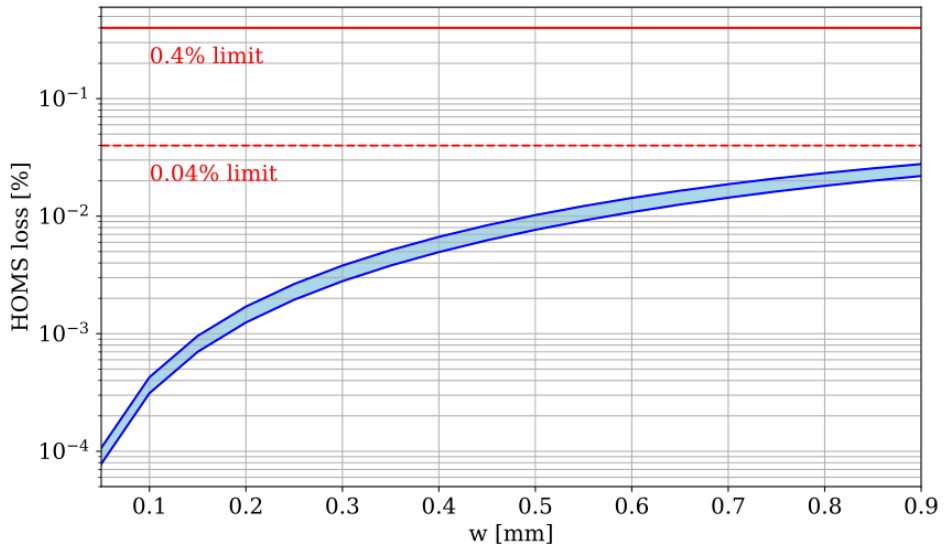


Fig.10. HOMS as a function of beam size

Higher order mode scattering (HOMS):

$$HOMS = 1 - \frac{\int E_{00}E_{00}^{\dagger}e^{-ik\Delta W}dxdy \int E_{00}^{\dagger}E_{00}e^{ik\Delta W}dxdy}{\left(\int E_{00}E_{00}^{\dagger}\,dxdy\right)^2}$$

5 Measurement: Actuation measurement

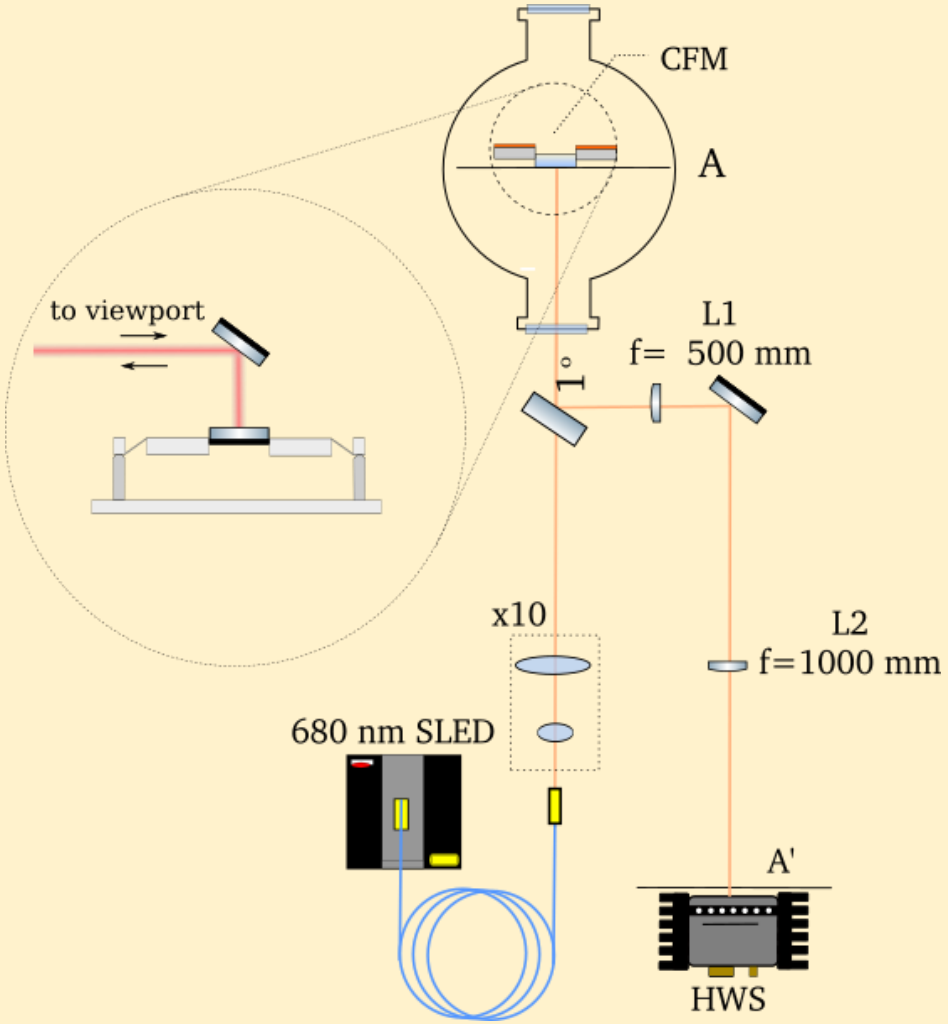


Fig.11. Schematic of experiment to measure actuation

Measuring system:

- **Imaging telescope:**
  - Magnification = 2
- **Heaters**
  - 400 Ohm AlN resistors connected in parallel mounted on the rear surface for tuning temperature
- **Vacuum chamber:**
  - Low vacuum (2.1 mbar) to cut out convection

5 Measurement: High dynamic range, linear response

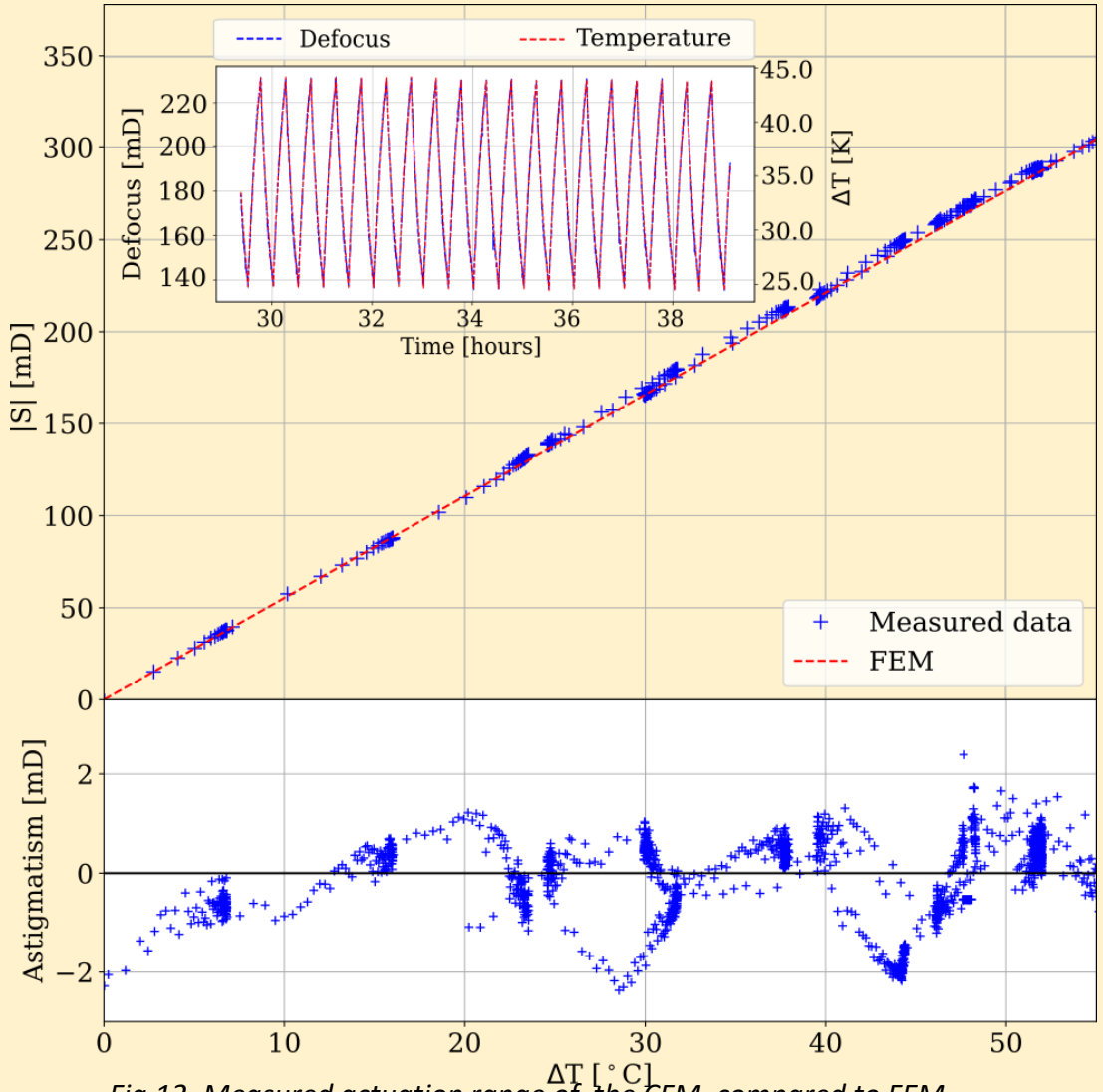


Fig.12. Measured actuation range of the CFM, compared to FEM

- Demonstrate **250 mD** actuation range with no sign of failure
- Highly **linear**:
  - Measured $\frac{\partial S}{\partial T} = 5.57 \frac{mD}{K}$
  - FEA $\frac{\partial S}{\partial T} = 5.53 \frac{mD}{K}$
- No apparent change in astigmatism:
  - Mean astigmatism: 0 ±2 mD
- **Highly reproducible** over 100 hours testing

6 Conclusion:

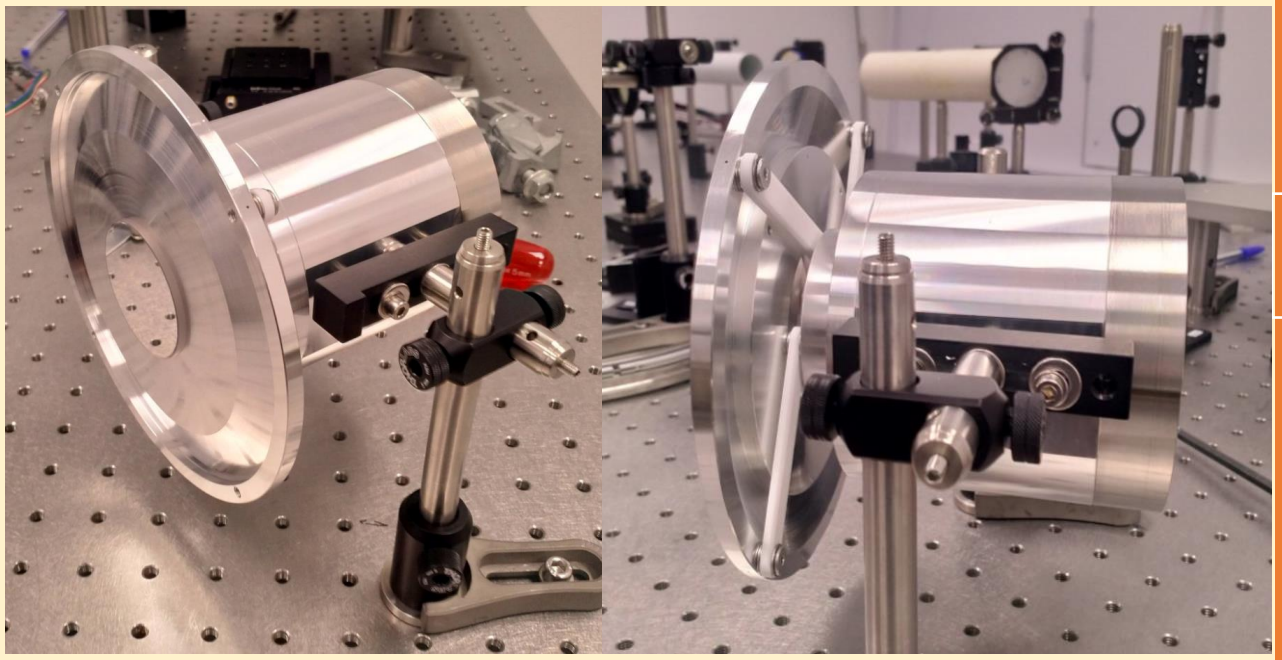


Fig.13. CFM assembly protype

Demonstrate a deformable mirror:

- High actuation range (>300 mD)
- Low aberration (<0.4% HOMS)
- No adhesive
- Linear response
- Simple and easily adapted to existing optics
- High reproducible

Ongoing work

- Displacement noise testing at MIT
- Improving noise and aberration of Hartmann system
- Integration into suspension system
- Preparing for installation by January 2021

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