The phase camera and mode mismatch challenges at Advanced Virgo

May 24 2023

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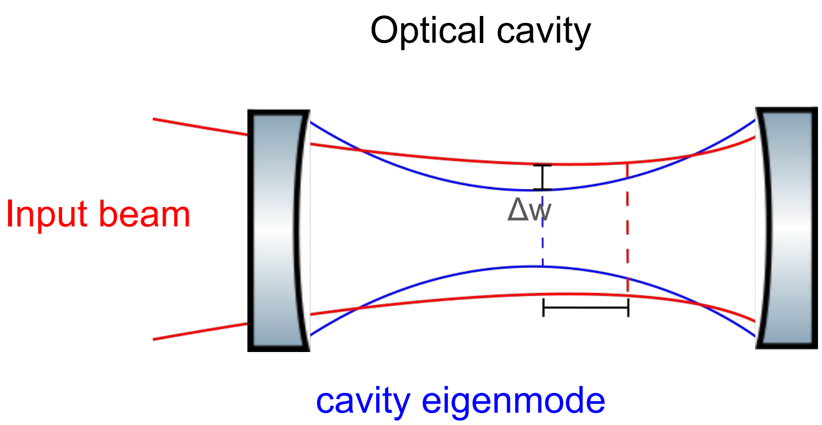
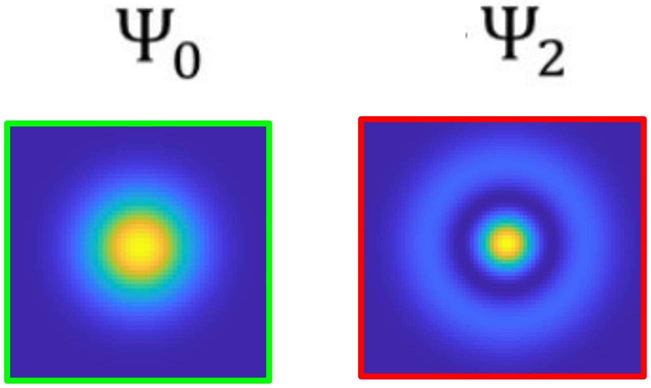
Gravitational-Wave Advanced Detector Workshop (GWADW) 2023, May 21-27 2023,
Hotel Hermitage, La Biodola, Isola d'Elba

What is mode mismatch ?





$$E_{\text{pos}} \propto \left[\Psi_0 + i\,\frac{b}{2kw_0^2}(\Psi_0 + \Psi_2)\right]$$

$$E_{\text{size}} \propto \left[\Psi_0 + \frac{\Delta w}{2w_0}\Psi_2\right],$$

The waist size of the input beam in the cavity is off by Δw and its waist position is off by b.

D. Z. Anderson, Appl. Opt. 23:17 2944-2949 (1984)

Why is mode matching important ?

- Losses must be minimised in order to optimize the effect of squeezed light in gravitational-wave detectors

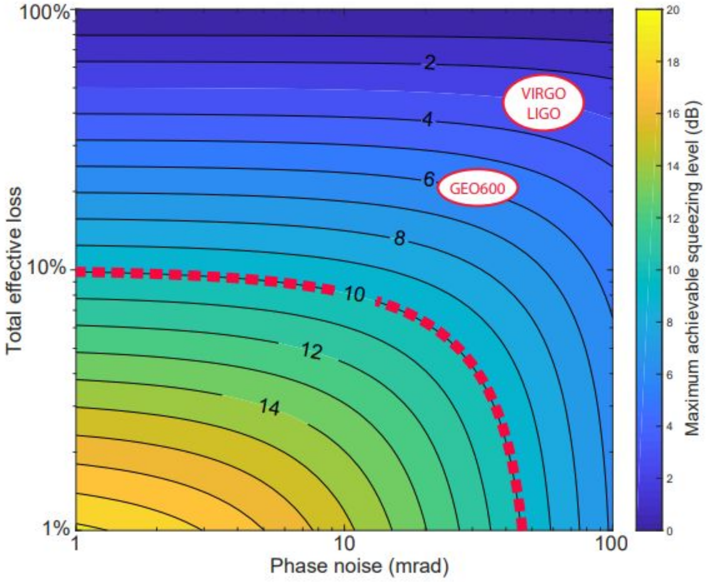
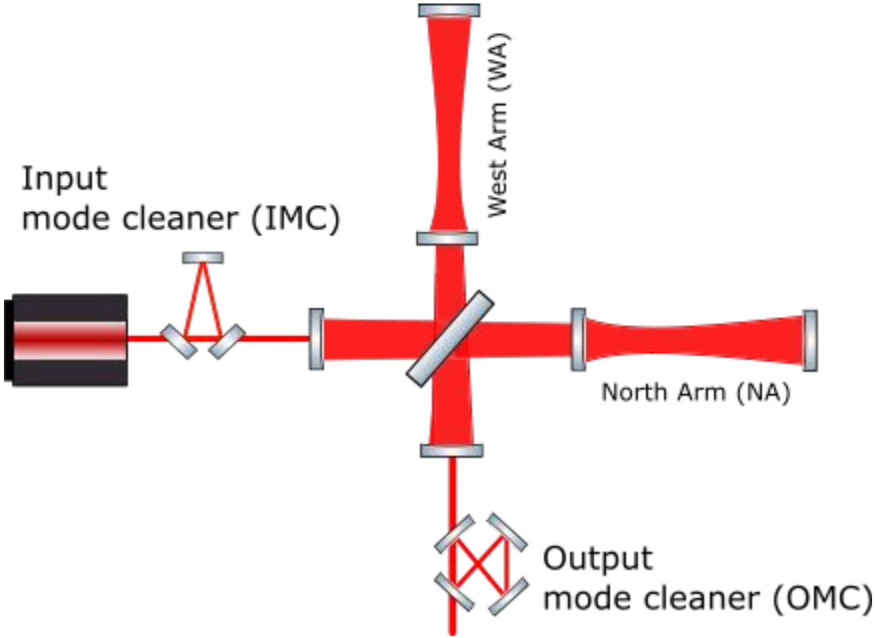


Image from ET Steering Committee Editorial Team 2020

- Tse et al. (2019): losses from mode mismatch and alignment make up to 40% of all optical losses at LIGO.

- E. Oelker, et al (2016): losses from mode mismatch need to be kept under 2% for achieving quantum limited interferometers.

Mode matching in Advanced Virgo



- We go from mm beam to cm beam.
- Eigenmodes of different cavities to match.
- Impacts stability of locks and detector sensitivity - sideband gain degradation, HOMs impact control signals (even more so with a marginally stable cavity).

Landscape of mode matching challenges in AdV

Single cavities

Mode match beam into…

- arm cavities.
- output mode cleaner
- (Squeezer) filter cavity
- And others, reference cavity, input mode cleaner, etc..

Coupled cavities

Mode match…

- sidebands and carrier in power recycling and signal recycling cavities (PRC and SRC)
- Squeezer beam into the interferometer

Optimising mode matching in AdV

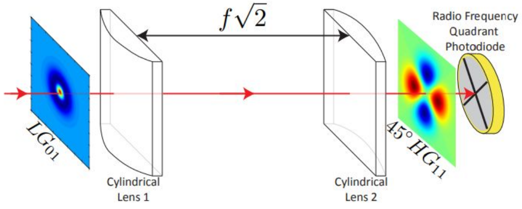
Single cavities

Mode match beam into…

- arm cavities.

Cavity FSR scan, mode mismatch is ratio of Ψ_2/Ψ_0

- (Squeezer) filter cavity



Coupled cavities

Mode match…

- sidebands and carrier in power recycling and signal recycling cavities (PRC and SRC)

Maximise sidebands PRC gain

Thermal compensation system tuning

Optimising mode matching in AdV

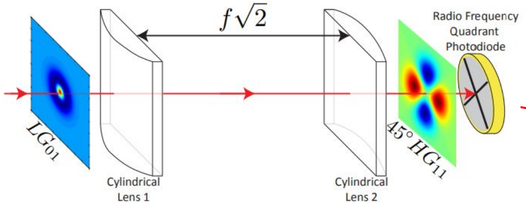
Single cavities

Mode match beam into…

- arm cavities.

Cavity FSR scan, mode mismatch is ratio of Ψ_2/Ψ_0

- (Squeezer) filter cavity



Basis not the same in practice!

Intensitive to astigmatism.

Coupled cavities

Mode match…

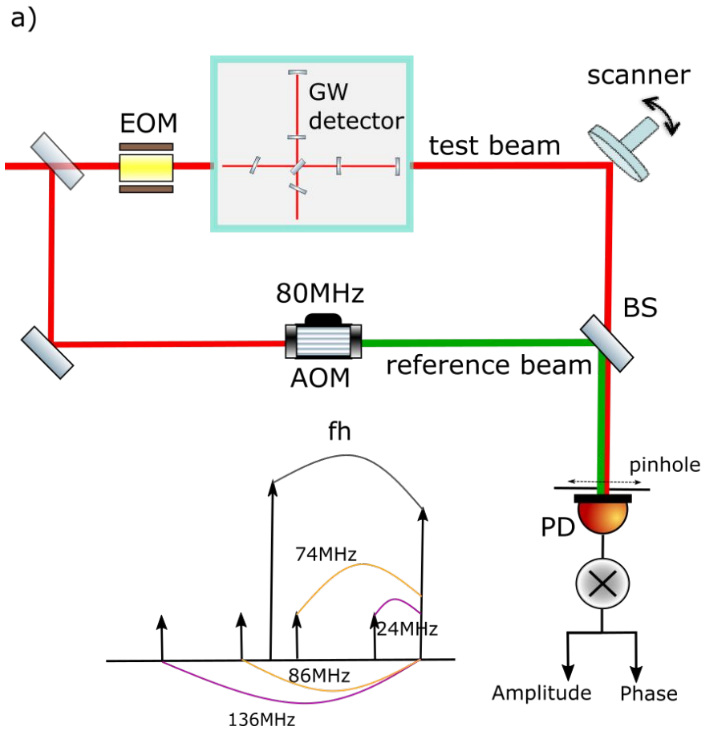
- sidebands and carrier in power recycling and signal recycling cavities (PRC and SRC)

Maximise sidebands PRC gain

Thermal compensation system tuning

Dependent on many factors, not just mode matching.

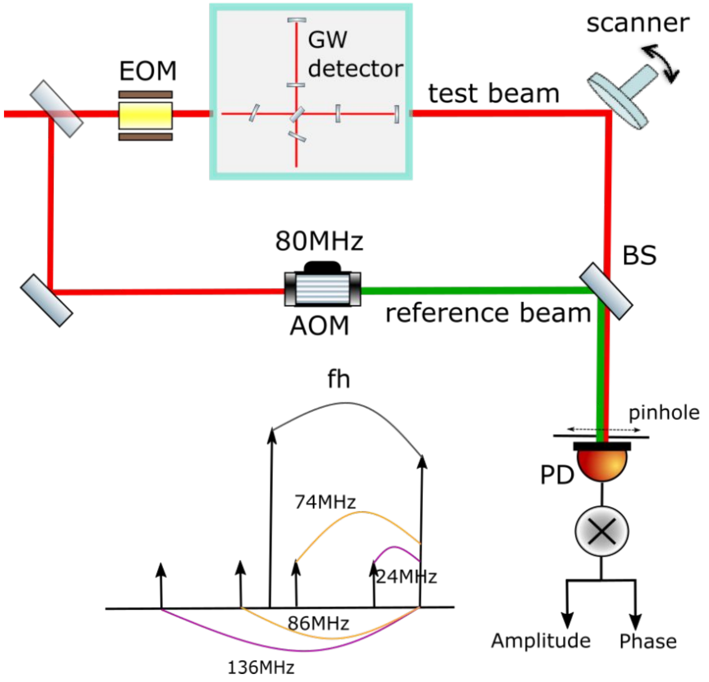
Phase camera (PhC)

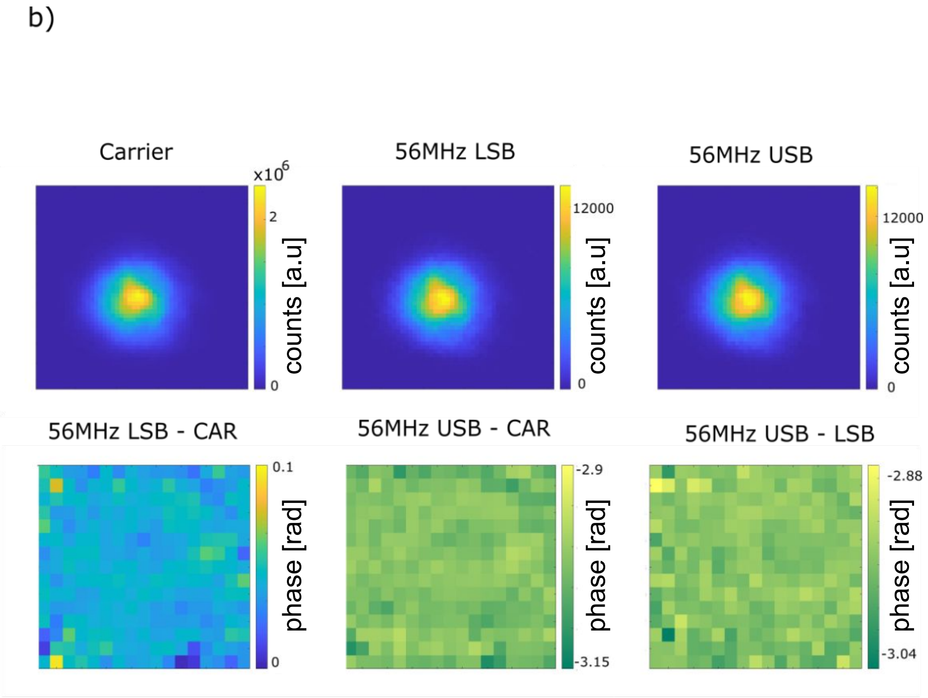


- The phase camera has access to the phase information - good for decoupling waist and size position mismatch.
- Access to higher order aberrations.
- Already installed and commissioned at Advanced Virgo.

K. Agatsuma et al., Opt. Express 27, 18533-18548 (2019)

Phase camera (PhC) - how it works



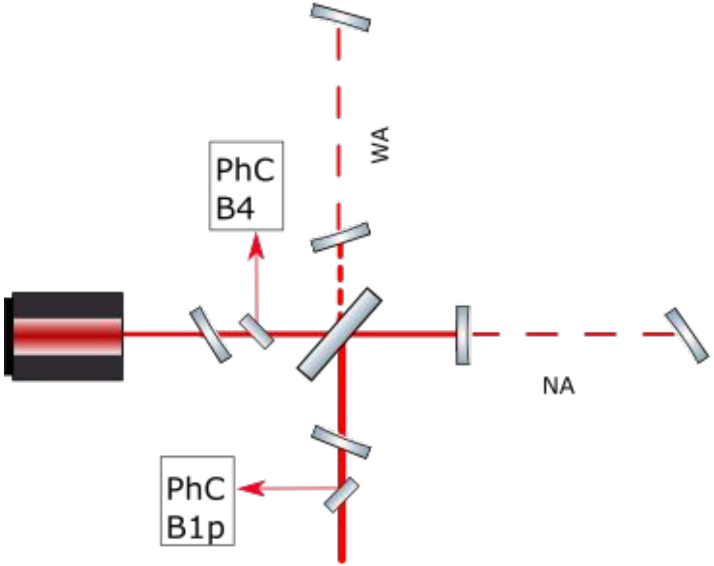


K. Agatsuma et al., Opt. Express 27, 18533-18548 (2019)

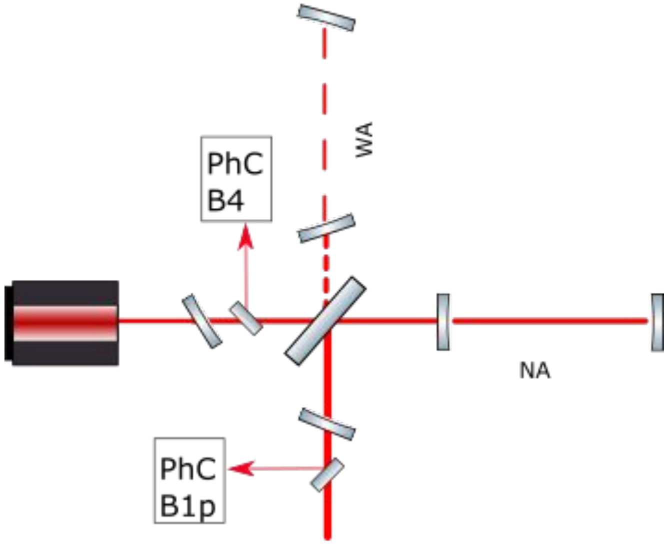
Differential phase images only - due to phase noise that the reference beam acquires along the optical fiber

Mode mismatch measurement with phase camera

- Measure input beam - single bounce from North arm (NA)



- Measure beam reflected from locked arm cavity (NA).

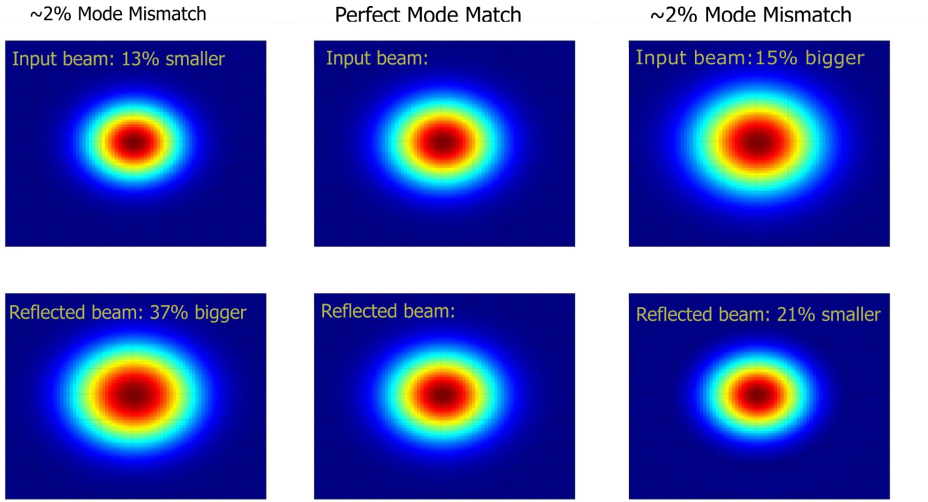


Phase camera data should be the same if mode matching is perfect

What we expect from simulations of the arm cavity

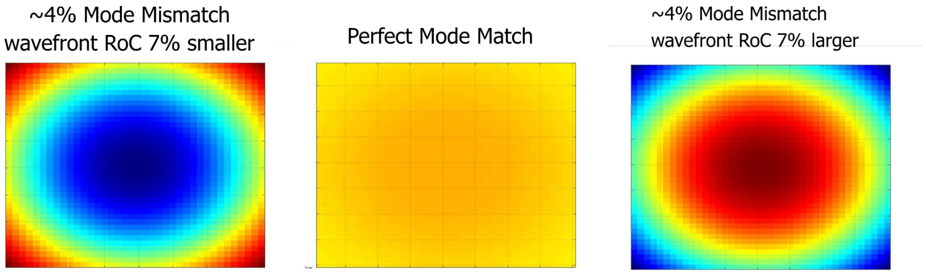
Amplitude images

detuning the radius of input beam



Differential phase images

detuning the radius of curvature of the input beam



- Simulations in OSCAR (Matlab FFT optics code)
  - Simulate locked single arm cavity with AdV parameters.
  - Detune input beam parameter - radius and wavefront radius of curvature - for small amounts of mode mismatch.

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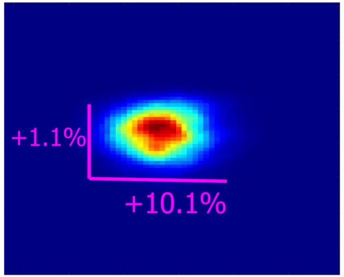
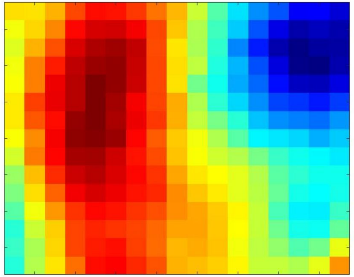
What we measured in AdV

<u>West arm</u>

Carrier intensity

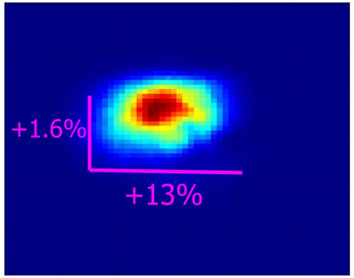


LSB56 - Carrier DPHI

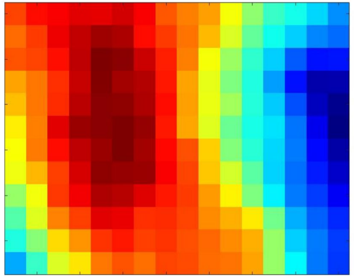


<u>North arm</u>

Carrier intensity



LSB56 - Carrier DPHI



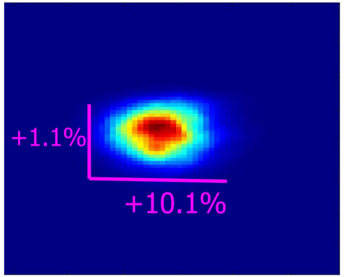
- Beams increase in size, bigger change for the North Arm (NA)
  - In agreement with mode mismatch measured with FSR scan: 2% NA, 1.2% WA

- Not expected the astigmatism (increase more significant in 1 direction)
- Not expected the elongation of the phase map

What we measured at AdV

West arm

Carrier intensity



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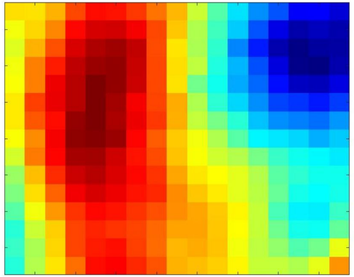
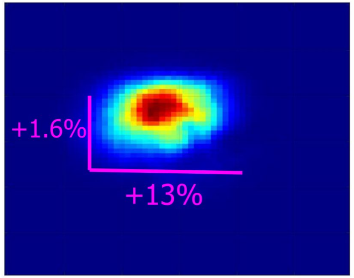
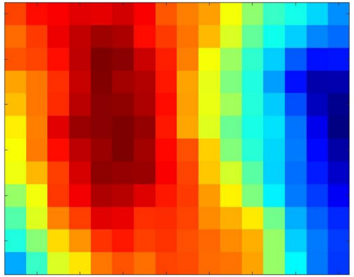


North arm

Carrier intensity



LSB56 - Carrier DPHI

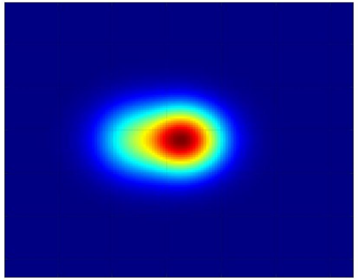


Adding a small misalignment of the end mirror (1urad hor. direction) + the mode mismatch

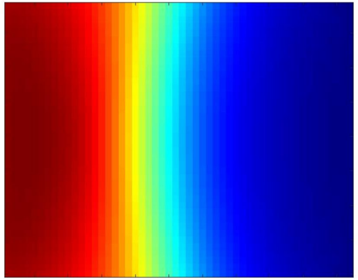
Could explain astigmatism and phase aberration ?

Simulation

Carrier intensity



LSB56 - Carrier DPHI



Probing the mode of the arm cavities

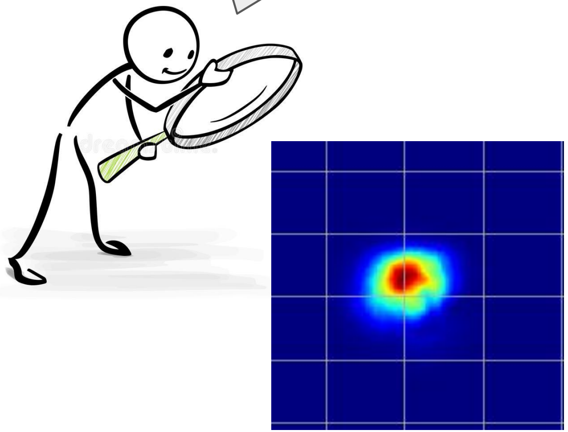
Besides comparing with simulations we can also look directly at the mode measured by the phase camera

Beams can be decomposed in a superposition of Hermite-Gaussian modes:

$$I(x,y) = \sum_{n}^{\infty}\sum_{m}^{\infty} c_{nm} H_n^2(x,\omega_0) H_m^2(y,\omega_0)$$

ω_0: Waist size of reference basis (fundamental mode)

c_{nm}: Complex coefficient



- According to simulation, if a tilt of the end mirror is responsible for the phase shape, the beam should have more first order mode content (HG_{10}) then second order!

Modal decomposition algorithm

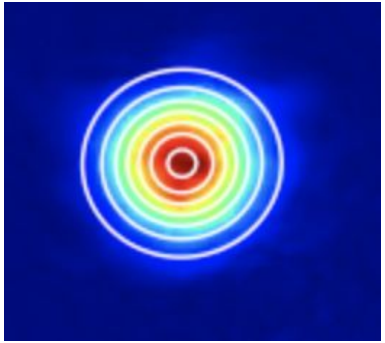
- Parameter space is reference basis, rotation angle and complex coefficients of HG modes included in the fit.
- Cost function is simply the difference between the generated image and the real data
- Minimisation of cost function by **Constrained Optimization By Linear Approximation (COBYLA)**:

M. J. Powel, Acta Numerica 7, 287-336 (1998)

  - Derivative free optimization
  - Computational cost depends on amount of HOMs included in fit
  - Can use custom conditions to constrain the parameter space

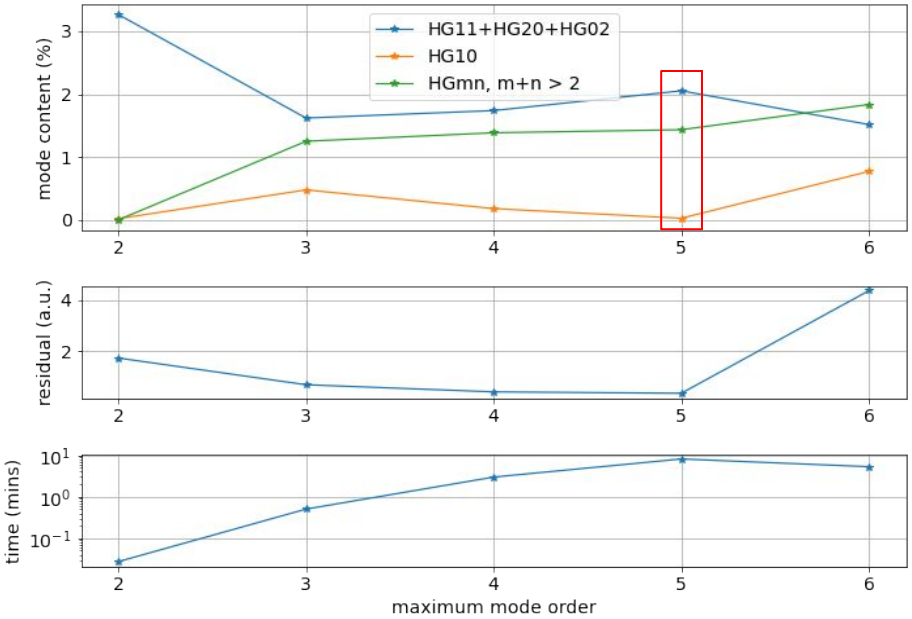
Allowed for rotations but fixed the reference basis.
Used single bounce beam as basis:

Gaussian fit

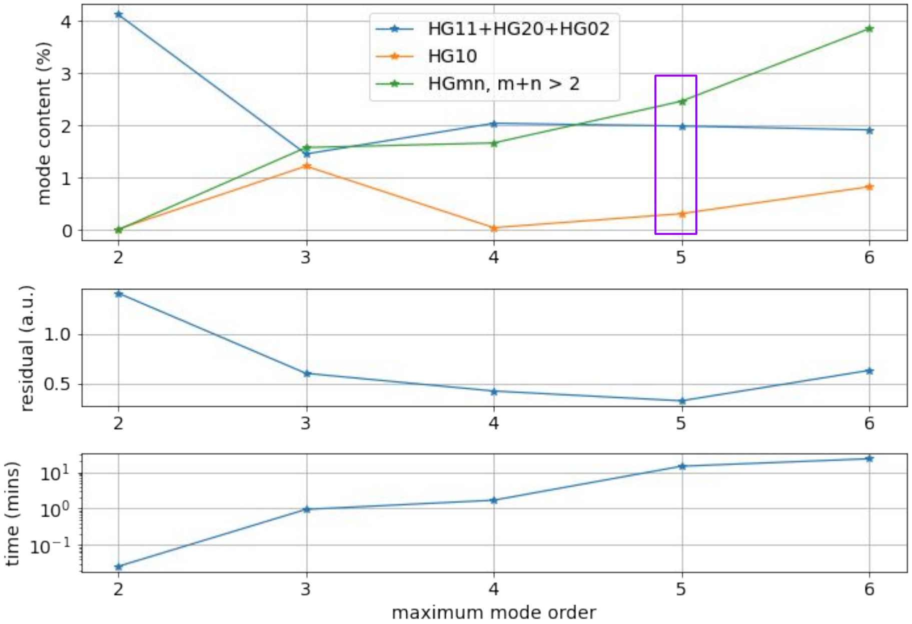


Modal decomposition - north arm

Fit A - constraint on fundamental mode:TEM00 > 95%



Fit B - constraint on fundamental mode:TEM00 > 90%



- Two solutions found with similar residual - <u>phase ambiguity ?</u>
- In both cases, <u>fit starts degrading as we include HOMs above order 5</u>

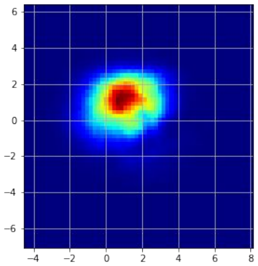
Modal decomposition - conclusions

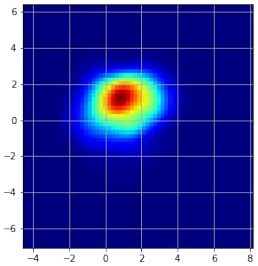
North arm

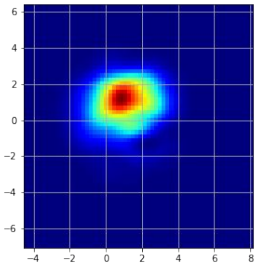
Fit A:
- **Residual: 0.41%**
- **Mismatch: ~2.1%**
- **HG10: ~0%**
- **HOMs: ~1.5%**

Fit B:
- **Residual: 0.35%**
- **Mismatch: ~2%**
- **HG10: ~0.4%**
- **HOMs: ~2.5%**

measurement





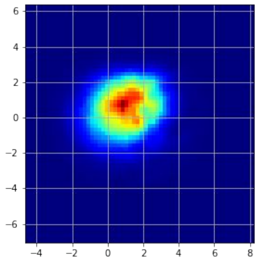


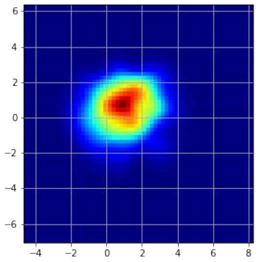
West arm

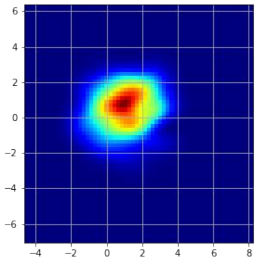
Fit A:
- **Residual: 0.42%**
- **Mismatch: ~1.6%**
- **HG10: ~0%**
- **HG01:~0.8%**
- **HOMs: ~2.1%**

Fit B:
- **Residual: 0.44%**
- **Mismatch: ~1.1%**
- **HG10: ~0%**
- **HG01:~0.8%**
- **HOMs: ~2.5%**

measurement

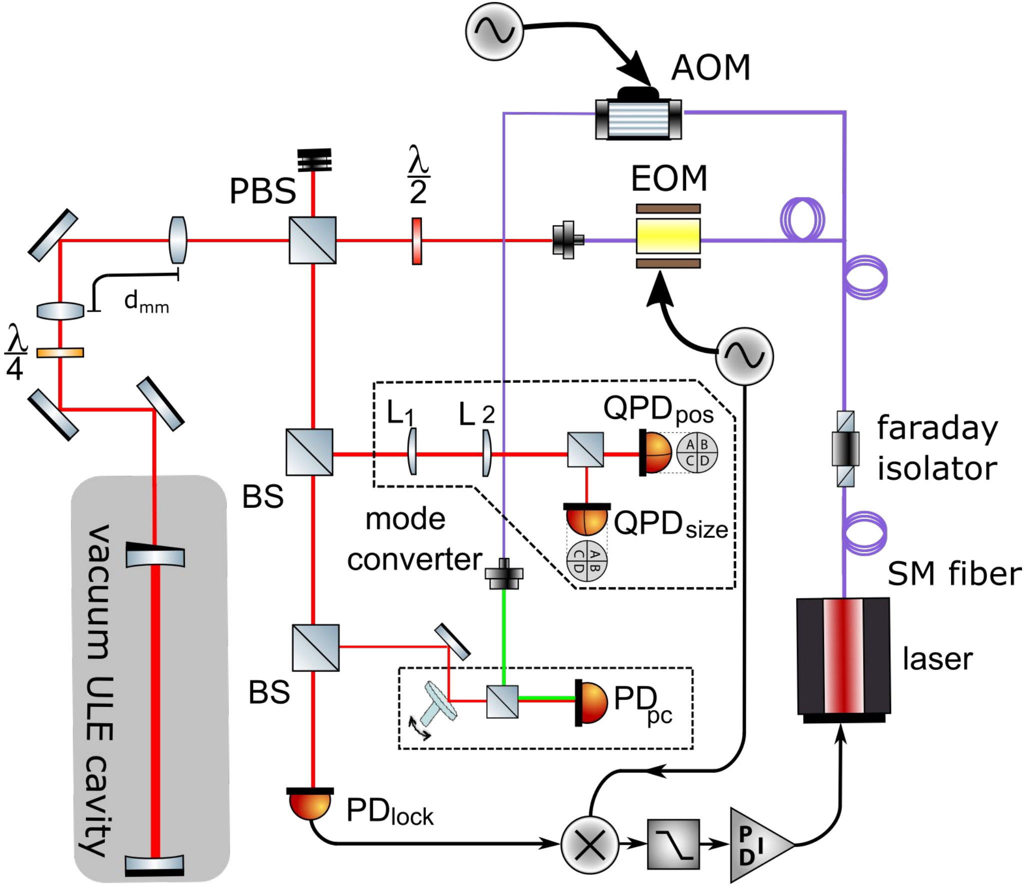






- Ambiguity between two solutions with similar residual
  - **Work underway to include differential phase images in the fit**
- Modal decomposition finds higher mode mismatch for North arm - agreement with FSR scan.
- Amount of HG10 is inconsistent with the tilted mirror hypothesis from simulation
- Amount of HOMs (up to order 5) similar to amount of mode mismatch .

Table-top set-up at UCLouvain



- Compare mode mismatch measurement by phase camera and mode converter.
- First linear cavity, then coupled cavity.
- Controlled environment to derive mode mismatch error signals from phase camera and use it on actuators, like piezo actuated lenses.

In collaboration with the NAPS research division of IMCN

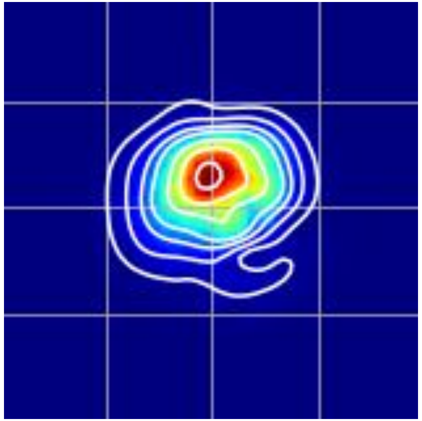
Summary and Outlook

- Studied the mode of the arm cavities using real data and modal decomposition:

- We plan to extend this kind of analysis to the power recycling cavity (when the central interferometer is locked, and in full lock)

- Modal decomposition and accurate simulations of phase camera images will help to understand better the phase images
  - The phase information should be especially important to help thermal effects diagnostics.

- Ambiguity between multiple solutions - work is under way to include phase images in the fit.

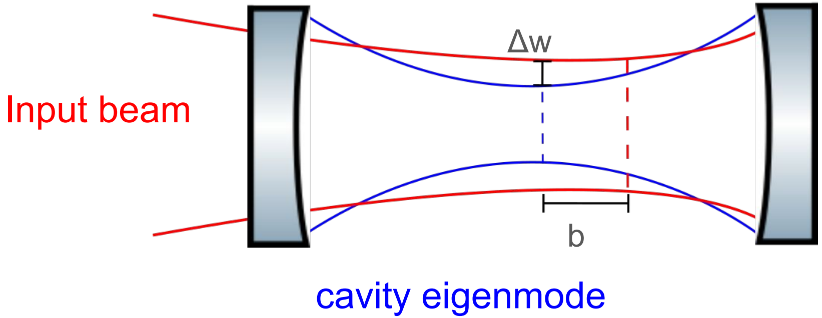


Fit B overlaid on amplitude image

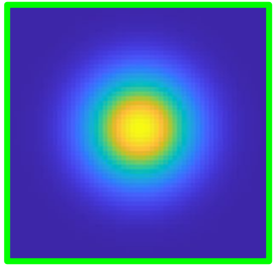
Extra slides

What is mode mismatch ?

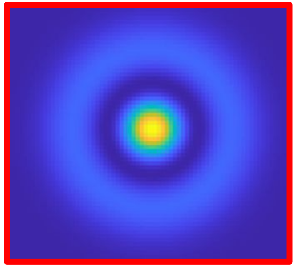
Optical cavity



Ψ_0



Ψ_2



Hermite-Gauss $$\Psi = H_m(x, w_0) H_n(y, w_0) e^{-j(\frac{k}{2q}(x^2+y^2)+\Phi)}$$

Laguerre-Gauss $$\Psi = (\sqrt{2}\frac{r}{2})^l L_p^l(r, w_0) e^{-j(\frac{k}{2q}r^2+l\phi+\Phi)}$$

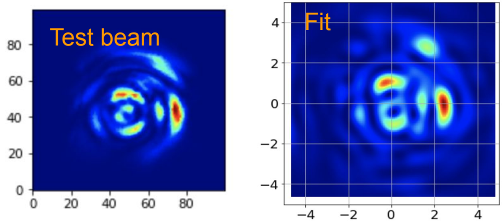
$$I(x, y) = \sum_m^\infty \sum_n^\infty c_{nm} \Psi_n^2 \Psi_m^2$$ Beam can be decomposed in either basis

Modal decomposition algorithm

We can validate the previous hypothesis by doing mode content analysis of the beam from the cavity

Already existing algorithm for modal decomposition:

- Parameter space is reference basis, rotation angle and complex coefficients of HG modes included in the fit.
- Cost function is the difference between the generated image and the real data (intensity image)
- Optimized using a Truncated Newton algorithm, which depends on derivatives.



$$I(x,y) = \sum_{n}^{\infty}\sum_{m}^{\infty} c_{nm} H_n^2(x,\omega_0) H_m^2(y,\omega_0)$$

- High computational cost
- Many times it converges before finding a local minima or fails to compute derivative

Same approach but using:
Constrained Optimization By Linear Approximation (COBYLA)

- Lower computational cost (can find solutions with less number of HOMs)
- Doesn't use derivative
- Often less precise
  - But can use constraints on the parameter space to improve fit/computational cost (educated guess)
- **Fixed reference basis (single bounce beam), allowed rotations**