Higher-order Laguerre-Gauss modes for future GW detectors: review of research status and strategies for the future

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on the behalf of the GW-group @ UofBirmingham

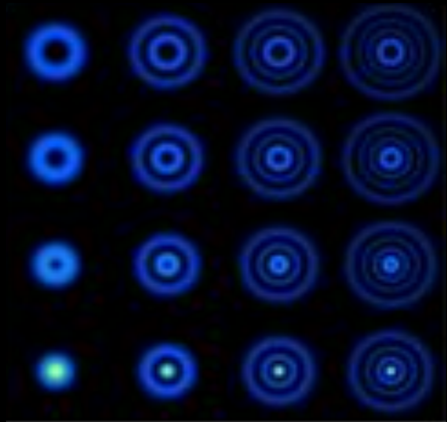
Einstein Telescope Meeting - Hanover 04.12.12

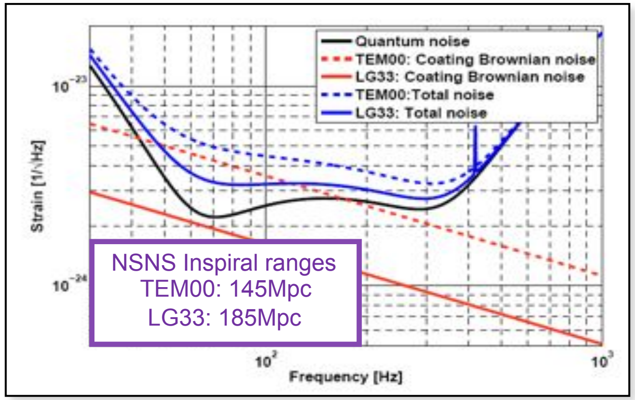
overview

- Why LG modes for GW detectors?
- Review of LG research
- Recent experimental results at prototypes
  - LG beams with 10m suspended cavity at JIF-Glasgow
  - LG beams at high laser power in Hanover

thermal noise reduction

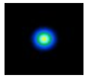
- Higher-order Laguerre-Gauss modes can reduce mirror thermal noise (bulk, coating)
- Technique promises to be compatible with other implemented and planned optical technologies



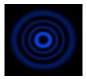


Chelkowski et al. PRD 79 (2009) 122002

Coating TN comparison



HG00: $S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\delta_C\,\frac{(1+\sigma)(1-2\sigma^2)}{\pi\,Y\,w^2}$



LGnm: $S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\delta_C\,\frac{(1+\sigma)(1-2\sigma^2)}{\pi\,Y\,w^2} \cdot \beta_n^m$

Improvement in h(t)

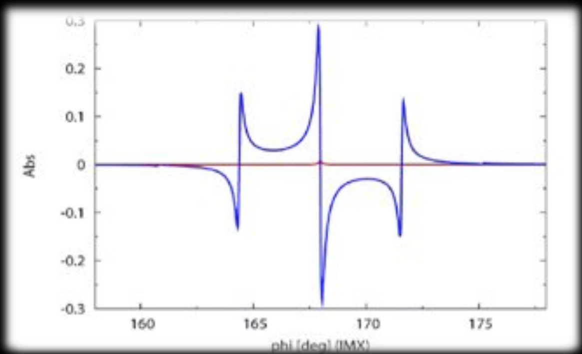
$$h_{33} = \frac{h_{00}}{2.7}$$

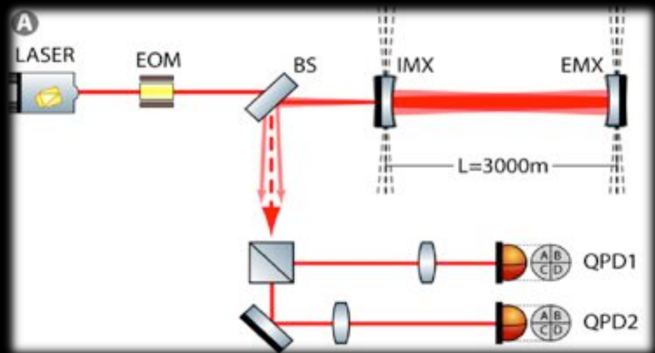
J.Y. Vinet, Living Reviews in Relativity, 12 (2009)

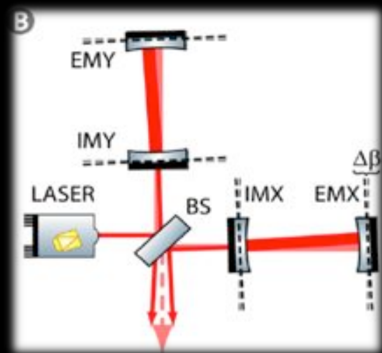
LG beams currently baselined in ET

earlier works…

- Analysis of compatibility of LG beams with current optical designs and interferometric schemes performed via numerical simulations (S. Chelkowski et al. PRD 79 122002 (2009))
- Simulation of length and alignment signals for simple cavity and Michelson interferometer
  - longitudinal control signals using Pound-Drever-Hall method
  - arm cavity alignment sensing & tilt-to-phase couplings in a km-scale cavity
    - no difference between LG_{00} and LG_{33} beams: error signals are effectively identical!
    - Standard control systems work without change!
- LG modes are fully compatible with current technology, and fully equivalent to HG_{00} (if not better)

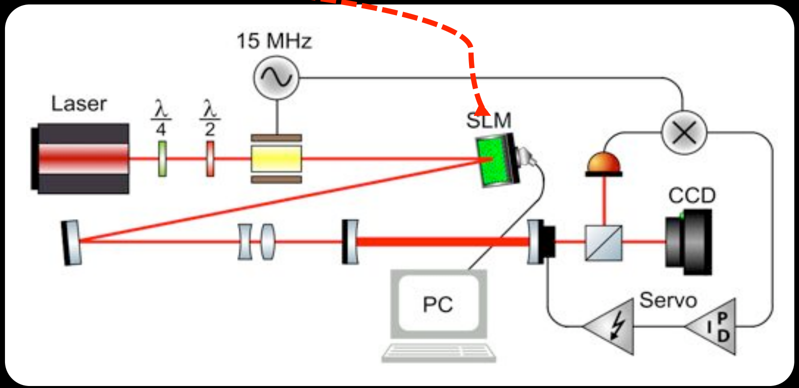






earlier works...

- 1st experimental demonstration of LG_{33} interferometry: P. Fulda et al, PRD, 82, 012002 (2010)
- Independent effort on MC/Michelson table-top demonstration: Granata et al. PRL 105, 231102 (2010)
  - Established LG generation method: HG_{00} + SLM or Phaseplate + Linear Mode Cleaner
  - Locked LG_{33} beam to a linear pre-modecleaner with Pound-Drever Hall, achieved stable LG_{33} beam with >99% purity

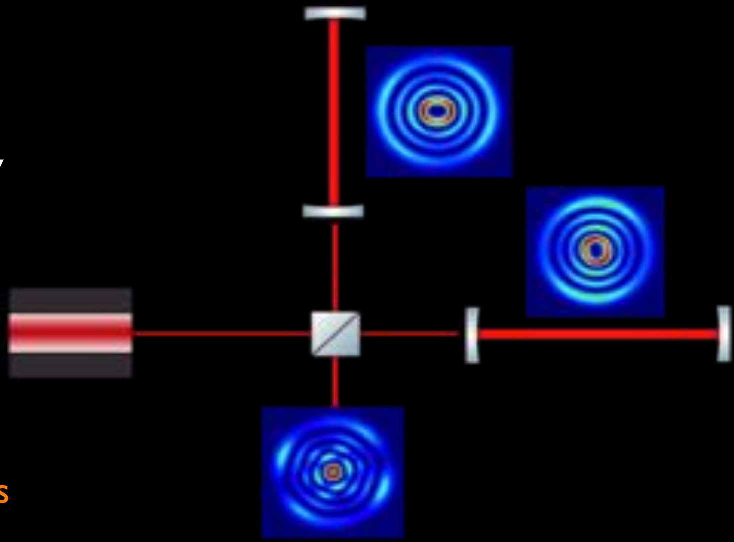


purity > 99%

LG interferometry is feasible

the mode degeneracy problem

- A cavity resonant for a selected higher order mode is also resonant for others of the same order *(2p+|l|)*
- A cavity pumped with a beam in a cavity-eigenmode will typically run in that mode, however small defects in the mirror cause coupling into unwanted modes
- The resulting contrast defect reduces the sensitivity
- 3 independent research efforts (Galimberti et al, Hong et al, Bond et al) applying realistic mirror surfaces in numerical models to show distorted beams
- Dark fringe contrast defect at beam splitter too large with current state-of-the-art surface quality

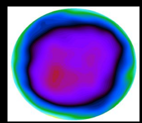
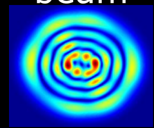
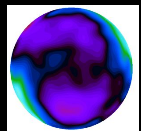
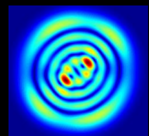
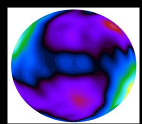
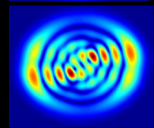


Other helical LG modes of order 9

mirror surfaces

- A detailed analysis using Zernike polynomials show that the worst coupling results from specific distortions at large spatial wavelength, strongly dominated by astigmatism
- Analytic framework to describing this coupling (C. Bond et al. PRD, 2011, 84, 102002)

all mirrors have the same spatial frequency content

	MIRROR	$Z_{2\pm2}$ content	Z_{20} content	Circulating beam	LG_{33} mode content [%]
BEST		0.494	0.506		78.54
AVERAGE		0.758	0.224		69.94
WORST		0.856	0.144		52.35

- This method could be used to generate mirror requirements for higher order LG
- In the particular example, limits to order 2 and order 4 Zernike polynomial's amplitude were sufficient to reduce impurity in the beam by a factor 100 (reduced from 114,000ppm with ETM08 to 815ppm)

raising the bar: LG beams in prototypes

Export beam conversion setup (phase plate + LMC) from table top experiment to prototypes

- Investigate LG_{33} mode behaviour in realistic large scale interferometer setup with suspended optics
- Investigate feasibility of LG mode generation at high laser power levels required by advanced detectors

Collaborations between with Glasgow and Hanover groups

University of Glasgow

AEI Hannover

tests at Glasgow10m prototype

- Inject LG_{33} mode in 10m cavity with suspended optics and full control at the JIF prototype in Glasgow, compare experiment with previous results
- Aim to investigate interferometric performance of higher-order LG modes compared to fundamental mode beams
- Aim to investigate effects from mode-degeneracy

B. Sorazu, P. Fulda, B. Barr, A. Bell, C. Bond, L. Carbone, A. Freise, S. Hild, S. Huttner, J. Macarthur, K. Strain

tests at Glasgow10m prototype

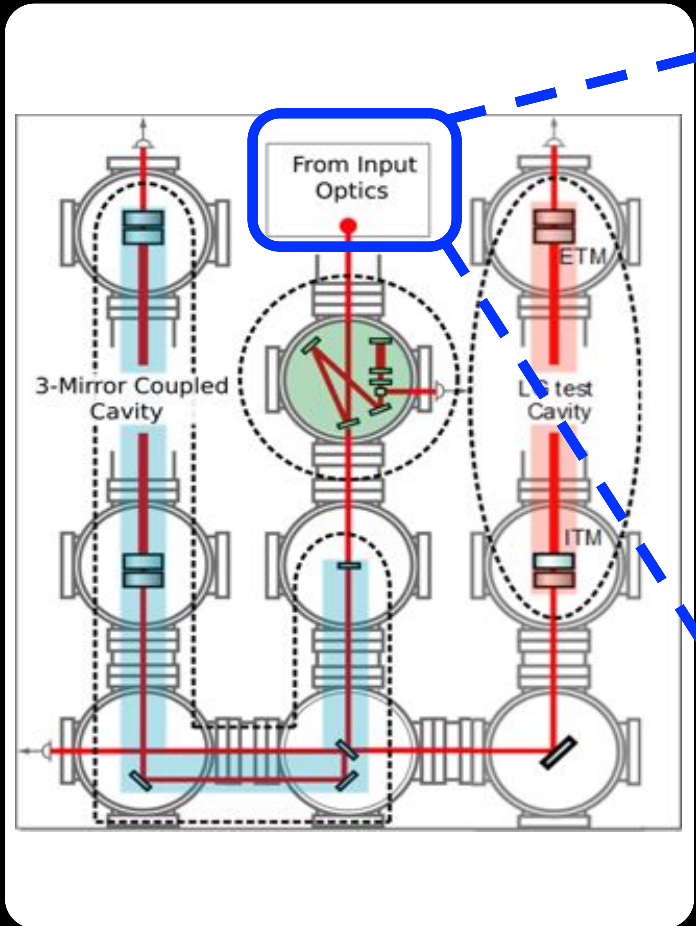
Extensive experimental campaign aimed to gain practical experience in handling higher-order LG beam in a cavity like those employed in real detectors.

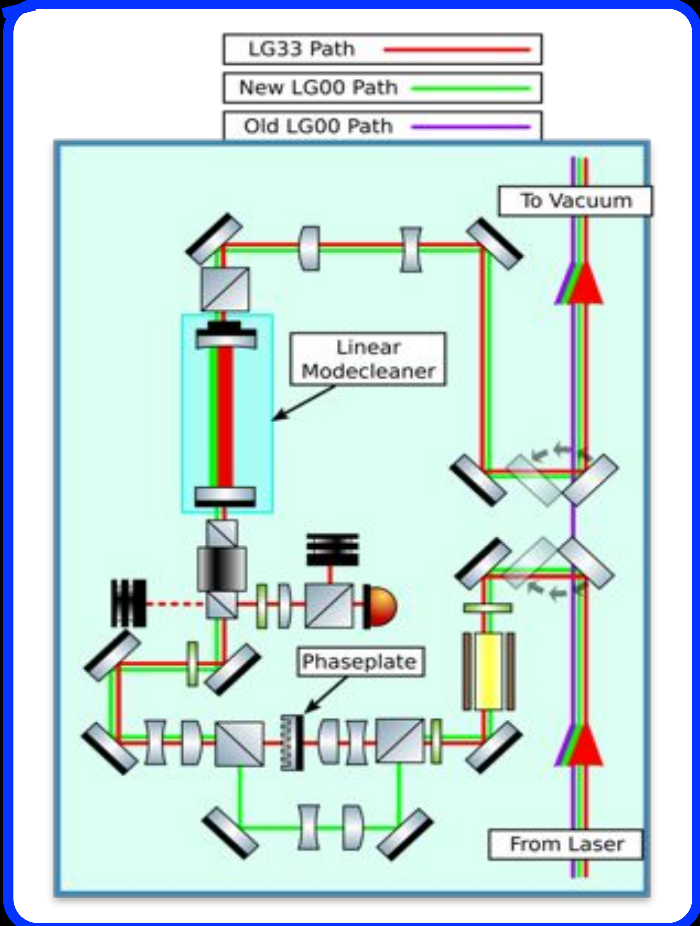
Several lessons learned and technical challenges identified:

- Astigmatism, mode-mismatch, interaction of transmissive optics

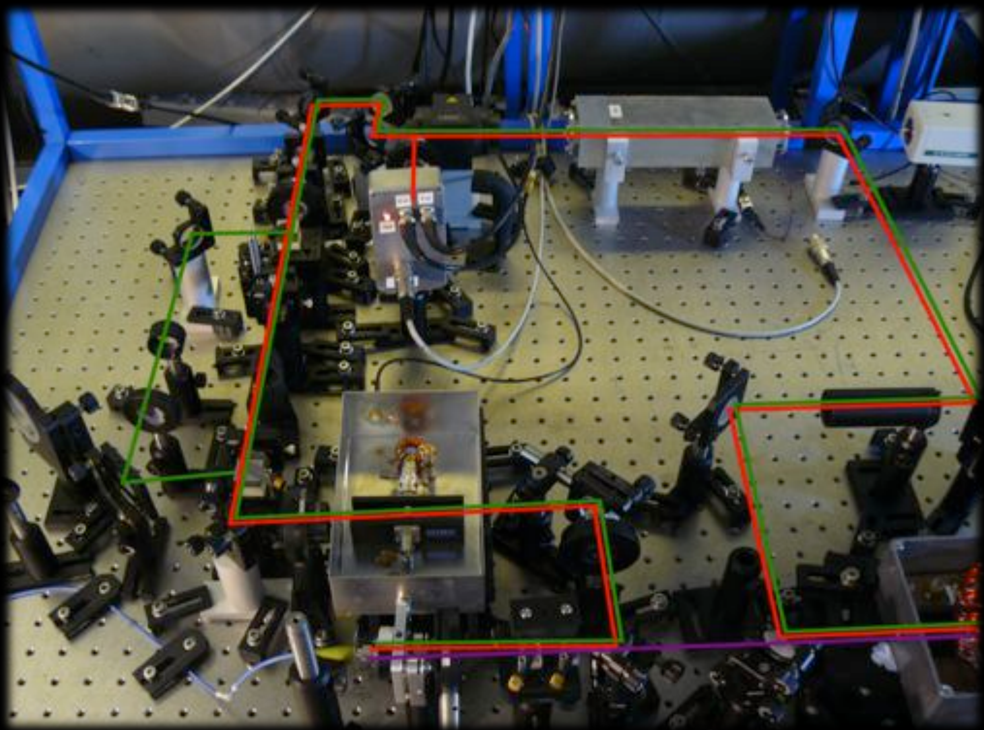
B. Sorazu, P. Fulda, B. Barr, A. Bell, C. Bond, L. Carbone, A. Freise, S. Hild, S. Huttner, J. Macarthur, K. Strain

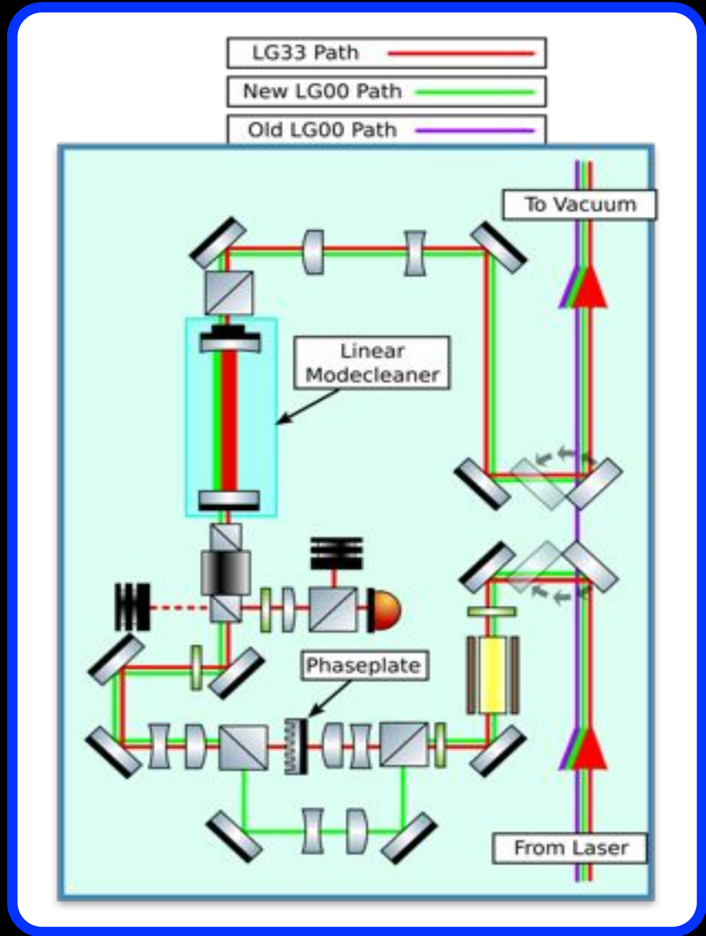
Optical Layout



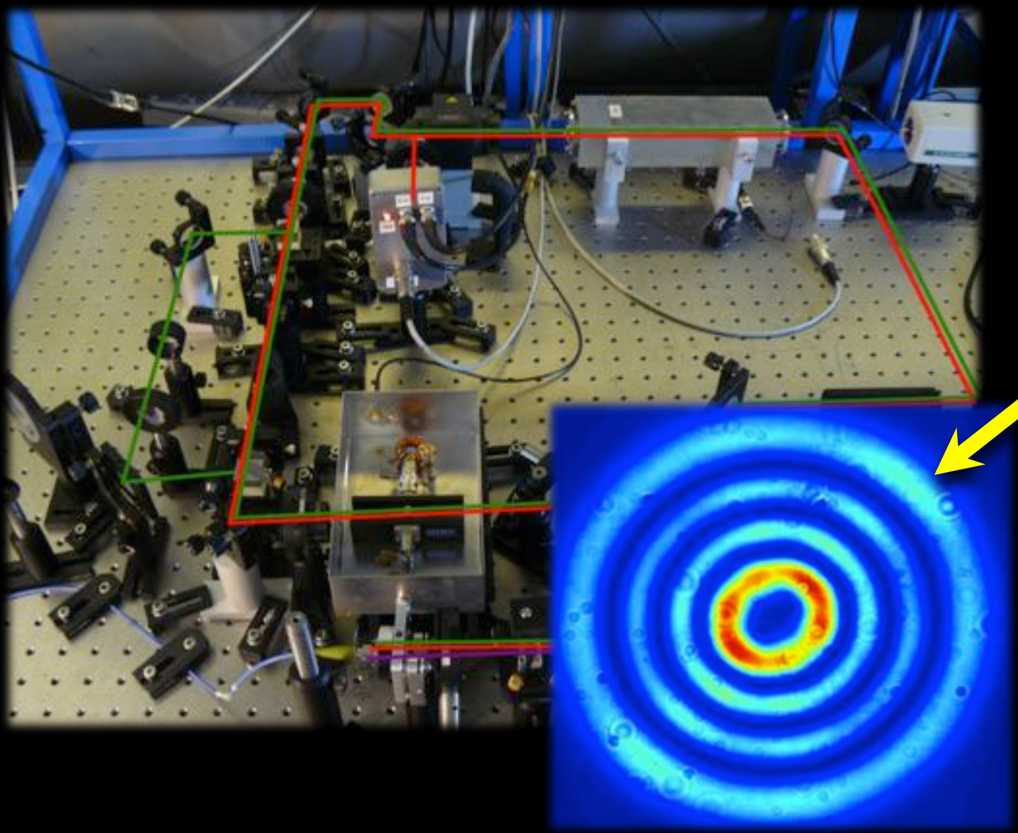


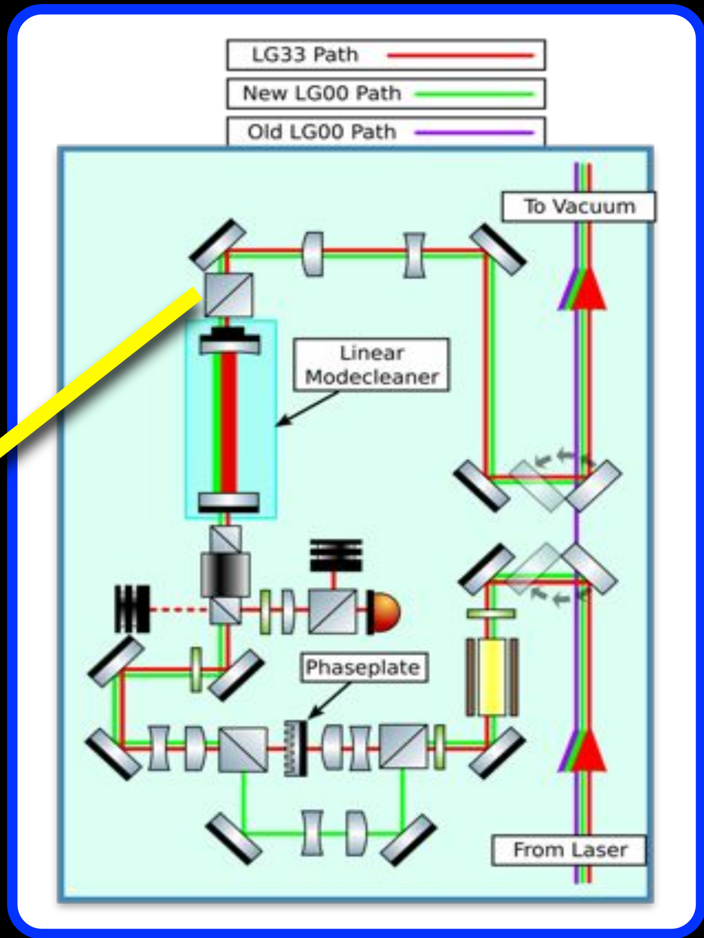
Optical Layout



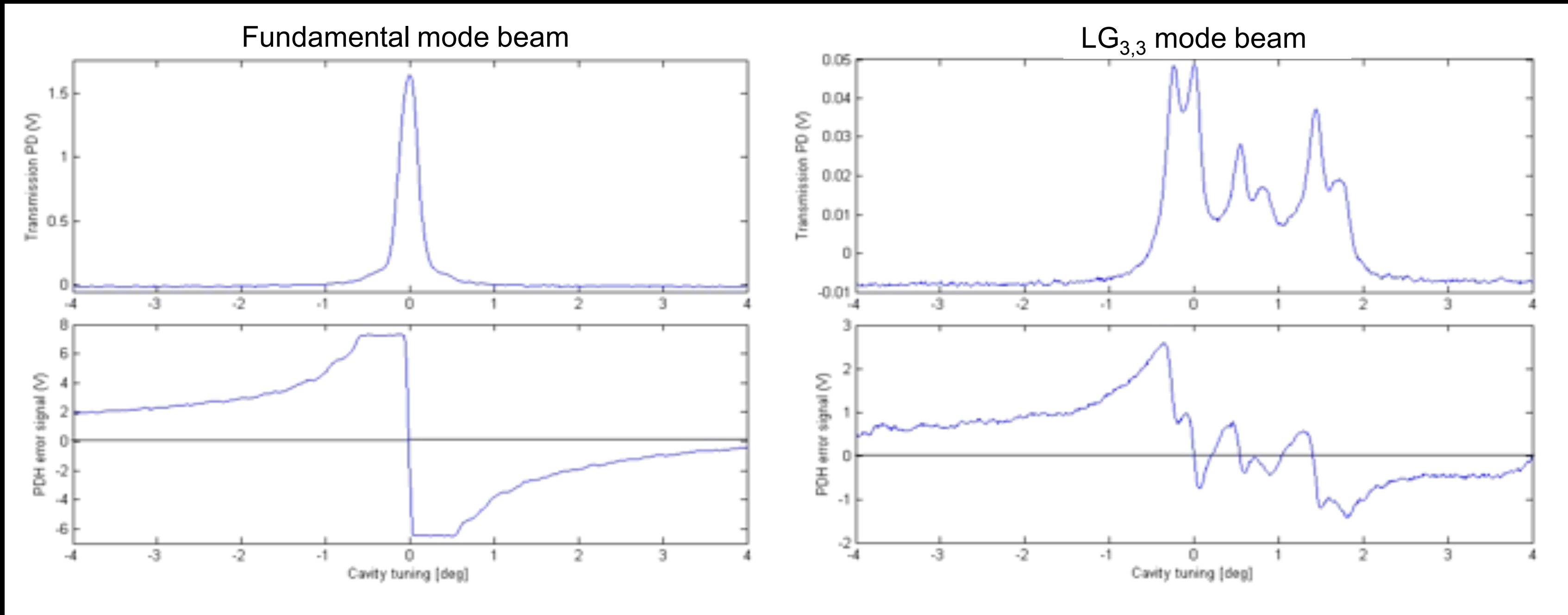


Optical Layout





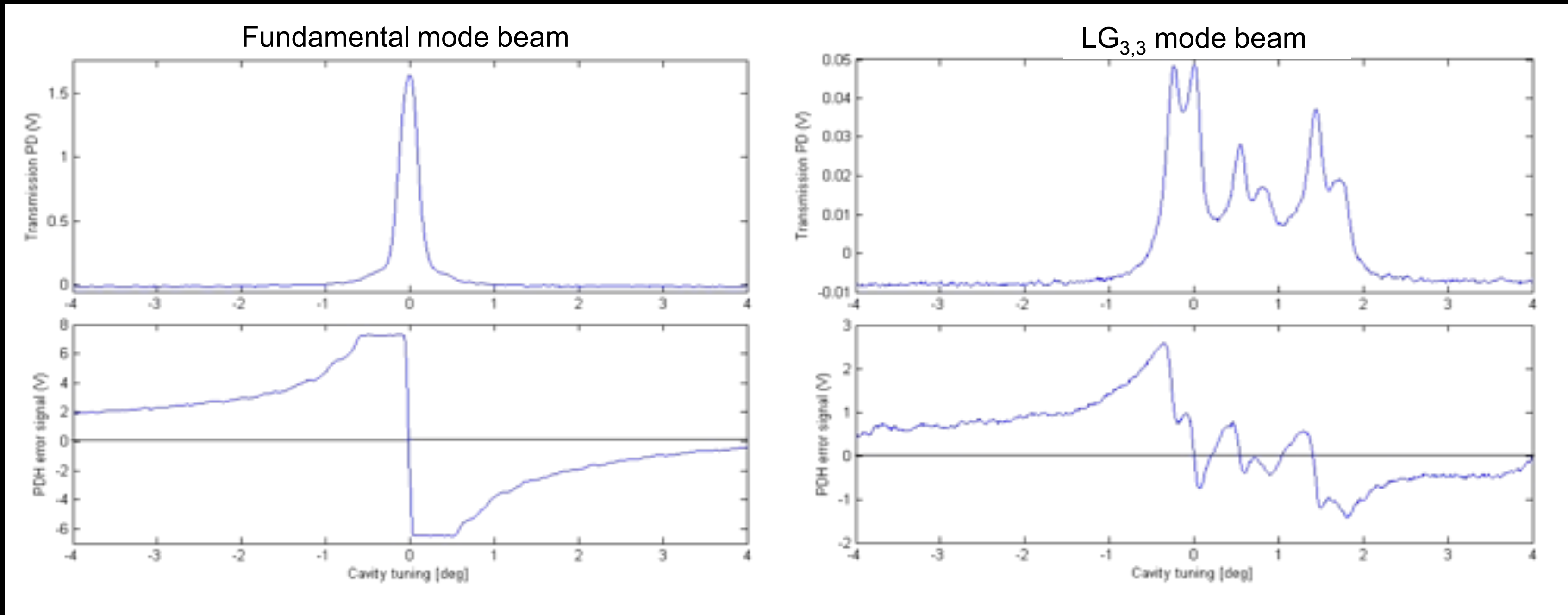
Comparison of interferometric performances



PDH signal presents multiple zero crossings:

- Linear range of error signal reduced → Harder lock acquisition
- Mode 'hopping' to nearby modes → Lock stability degraded

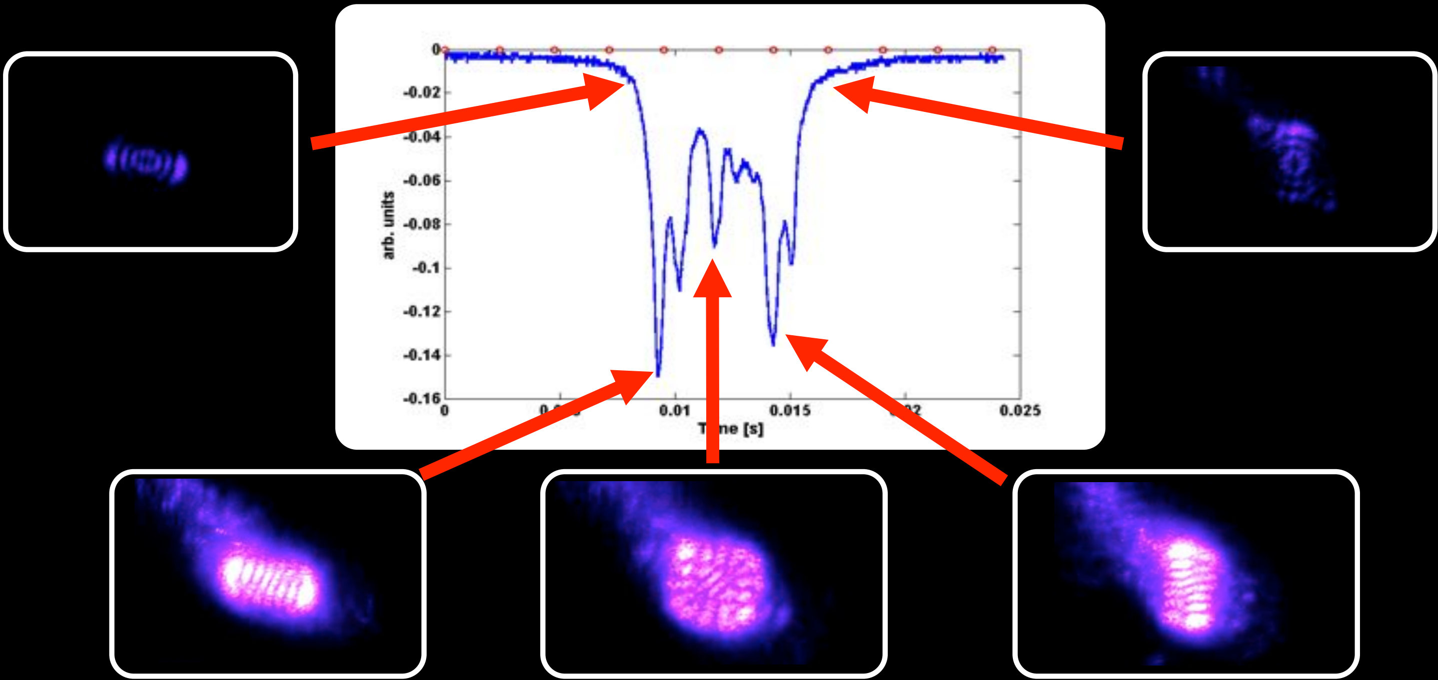
Comparison of interferometric performances



Frequency splitting of cavity resonance originating in astigmatism in the cavity mirrors. FINESSE simulations show:

- freq. splitting was determined by the amount of astigmatism added.
- the asymmetry of the freq. splitting is determined by the cavity misalignment

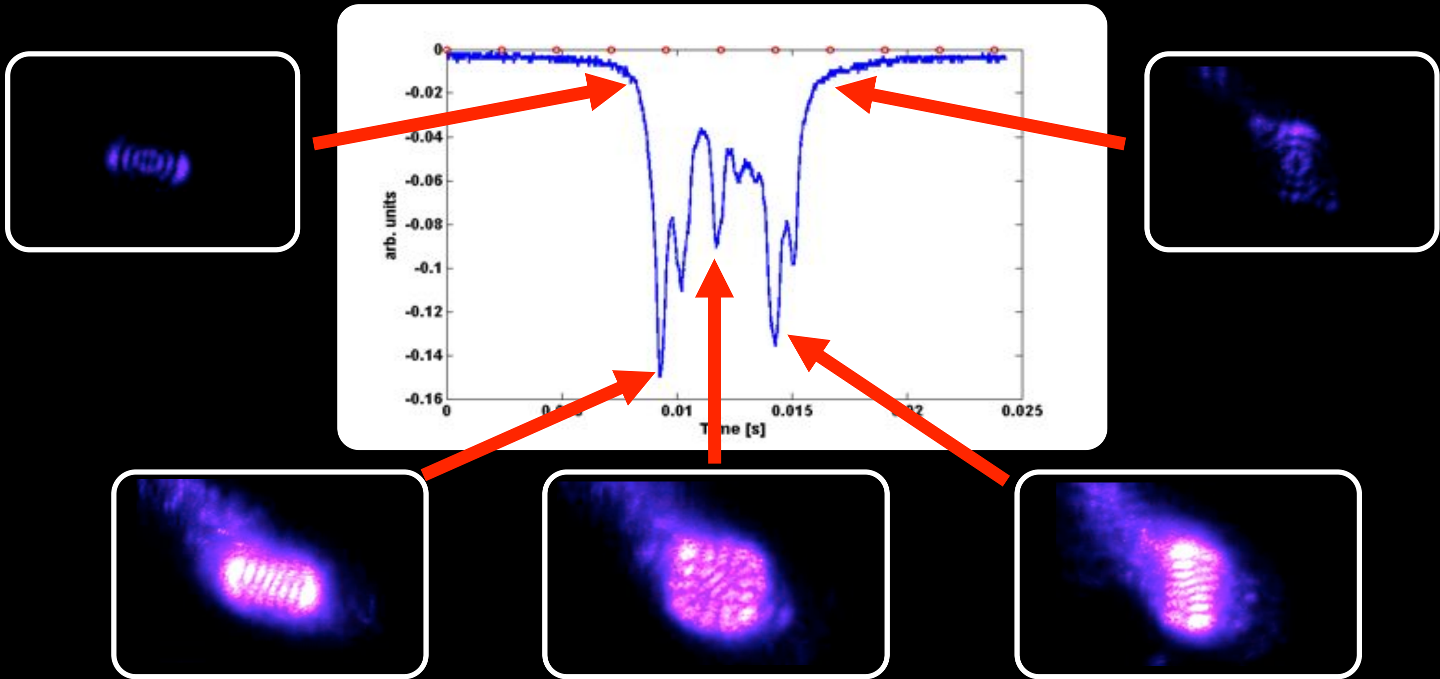
Scanning the cavity



Beam image analysis shows that astigmatism breaks the cylindrical symmetry required for LG modes!

Derive requirements for tolerable mirror astigmatism

Scanning the cavity

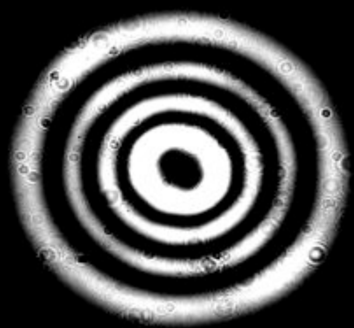


Beam image analysis provides evidence of non order 9 modes dominating in the cavity (get mainly order 7 instead!): caused by mode-mismatch → requirements!

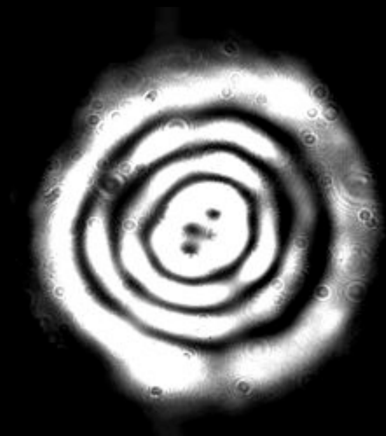
some additional useful information: beam degradation through transmissive optics

- LG_{33} beam quality reduced on passing through the input optics
- Degradation due to LG_{33} profile being much wider than HG_{00} for which the system was designed

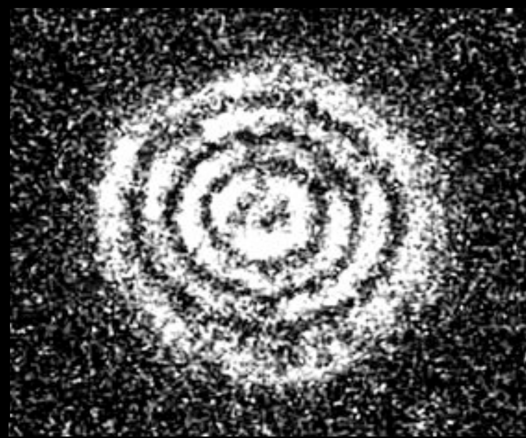
Contrast enhanced for visibility



Directly after the linear mode cleaner



After electro-optic modulator and Faraday isolator



Transmitted through cavity end mirror (cavity misaligned)

Clipping is a more likely problem with LG_{33} mode

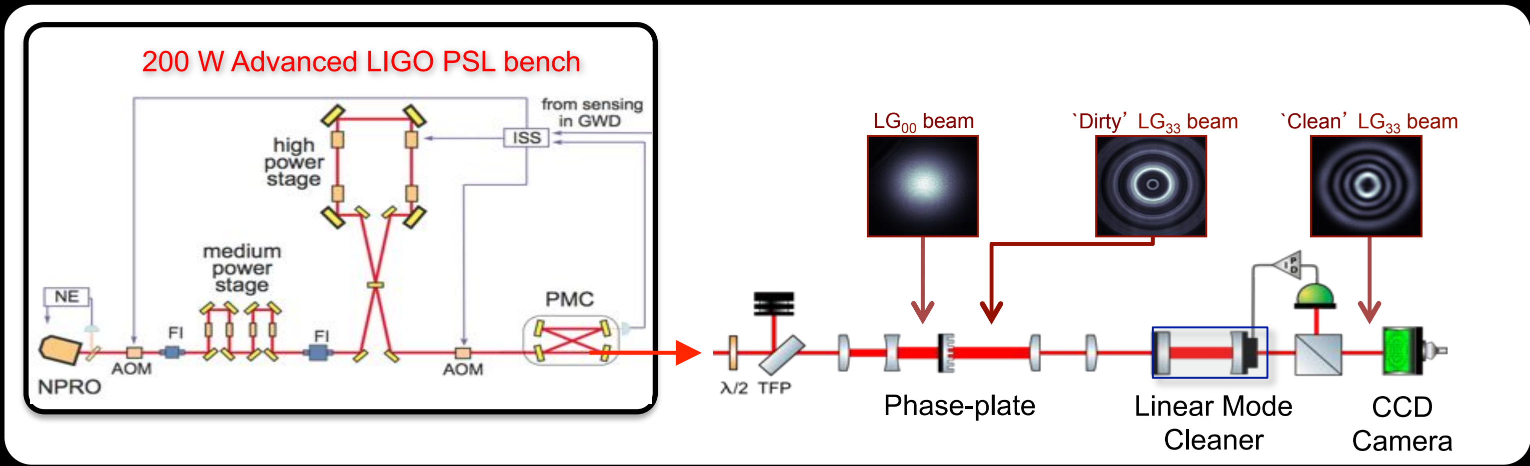
AEI Hannover

LG modes at high power

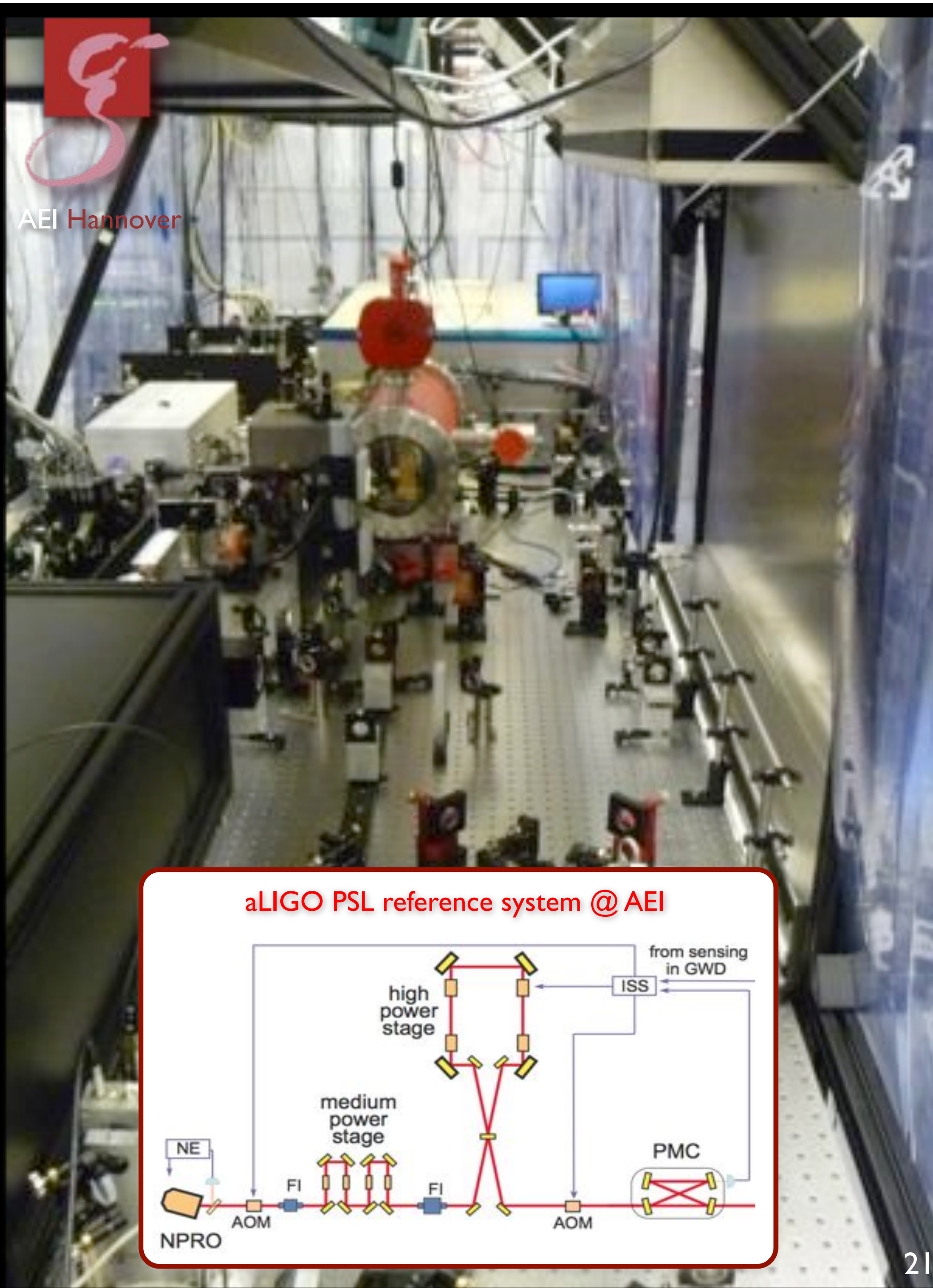
- Integrating LG_{33} generation into an aLIGO PSL reference system at AEI
- Experimental demonstration of high-power LG_{33} beam
- Test for thermal problems at converting phase-plate and for intra-cavity beam distortions

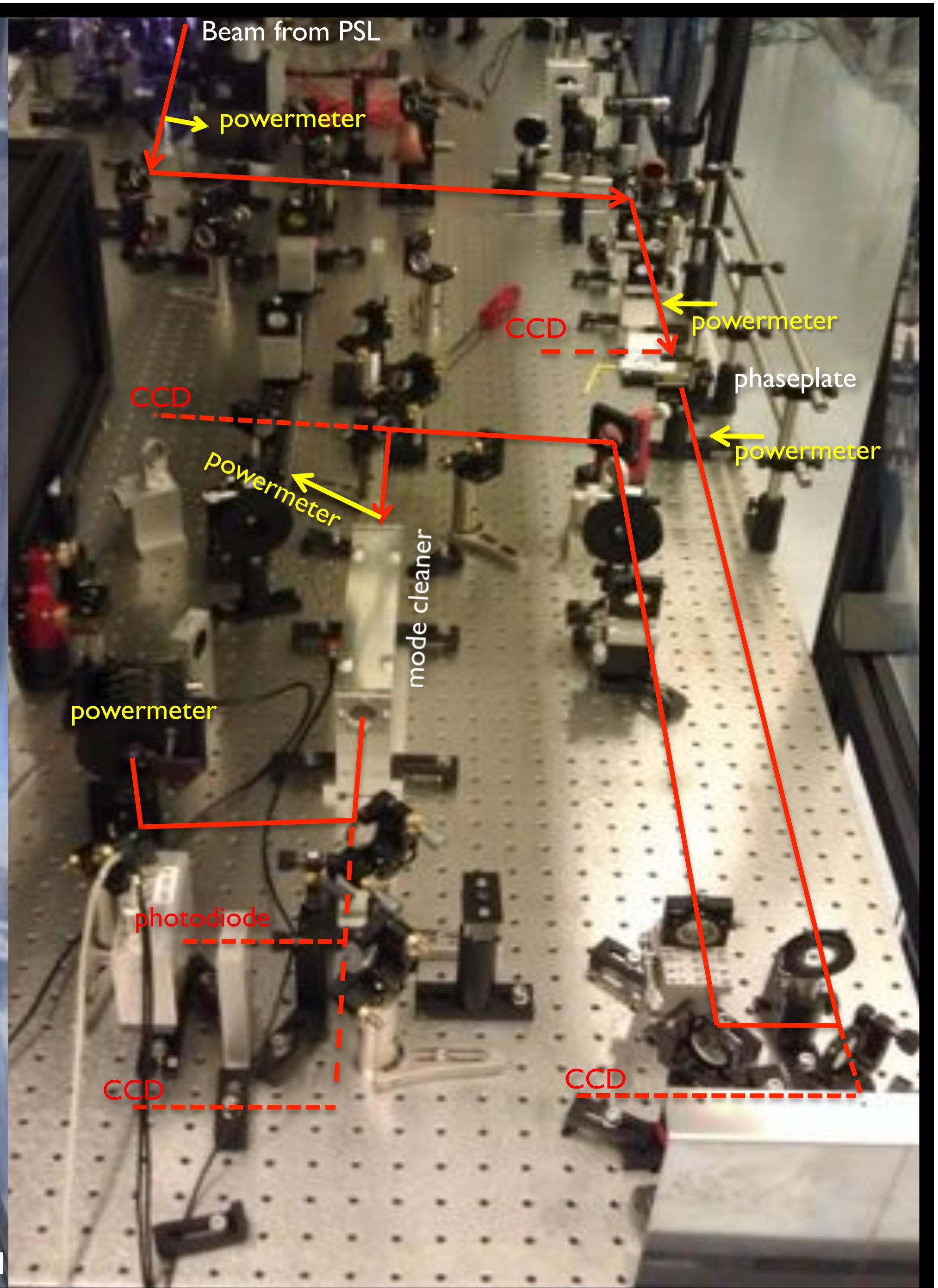
L. Carbone, C. Bogan, B. Willke, P. Fulda, A. Freise, K. Danzmann

optical layout



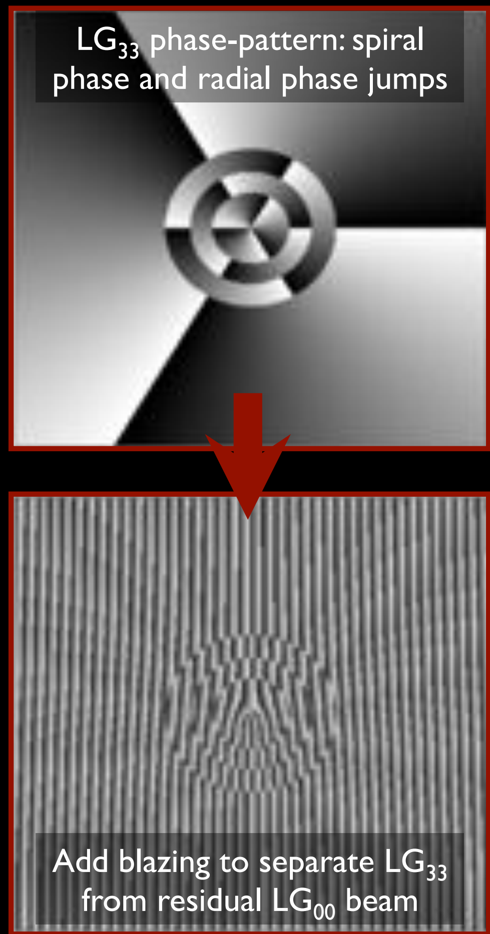
- Use the aLIGO 200W laser as input to our standard LG_{33} conversion setup: phaseplate + pre-modecleaner
- Laser output can be tuned for testing mode conversion for different powers


AEI Hannover
aLIGO PSL reference system @ AEI
from sensing in GWD
ISS
high power stage
medium power stage
NE
FI
FI
PMC
NPRO
AOM
AOM


Beam from PSL
powermeter
powermeter
CCD
phaseplate
CCD
powermeter
powermeter
mode cleaner
powermeter
photodiode
CCD
CCD

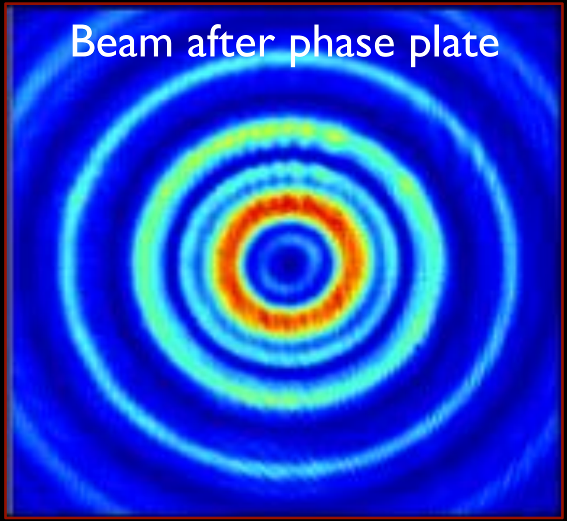
test of the mode-conversion method

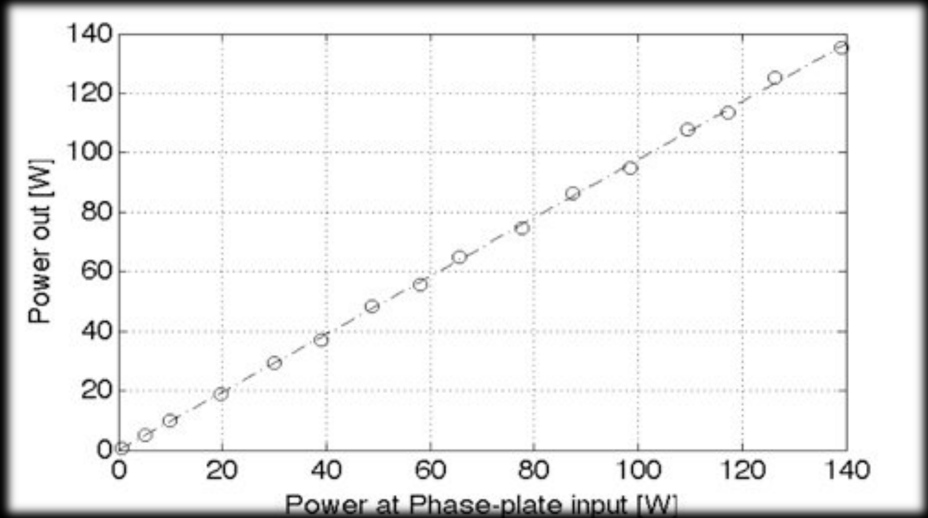
- Fused silica etched diffractive phase-plate, 3000×3000 pixels, 7×7um^2 size, 8 levels of phase modulation, 1064nm AR coating on both sides
- *nominal* LG_{33} conversion efficiency > 75 % (manufacturer's estimate)
- *optimal* conversion at waist of 3.5 mm radius LG_{00} beam
- >95% of input power in main diffraction order, ~ 4% in other diffraction orders, <0.2% reflected
- guaranteed up to 20W by manufacturer



high-power conversion

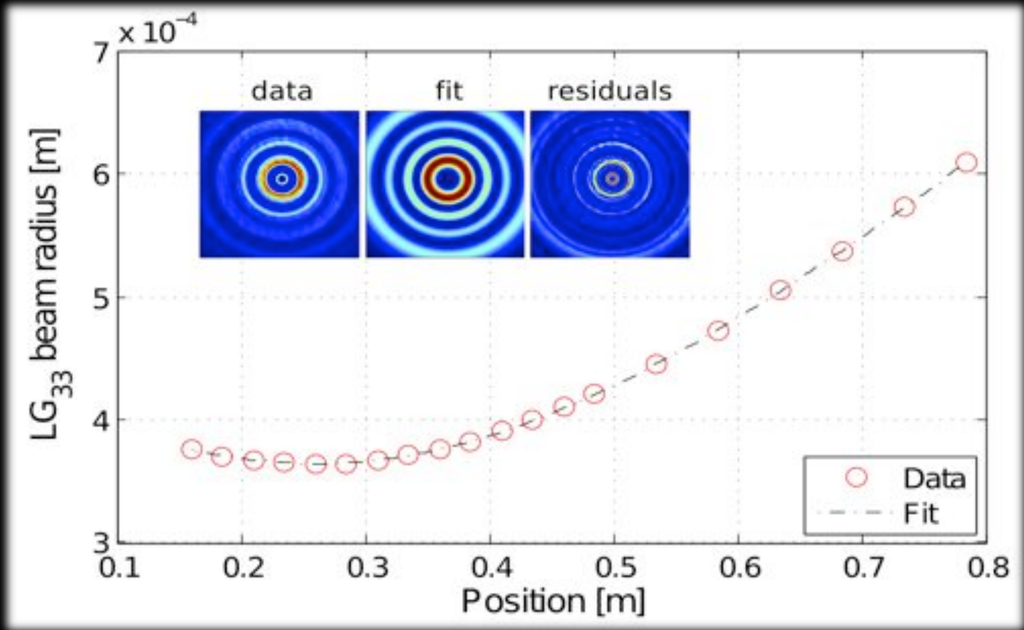
- Direct measurement of converted beam at the phase plate
- Stable conversion up to maximum available incident power of 138W
- Linear response and no degrading of phase plate at high power

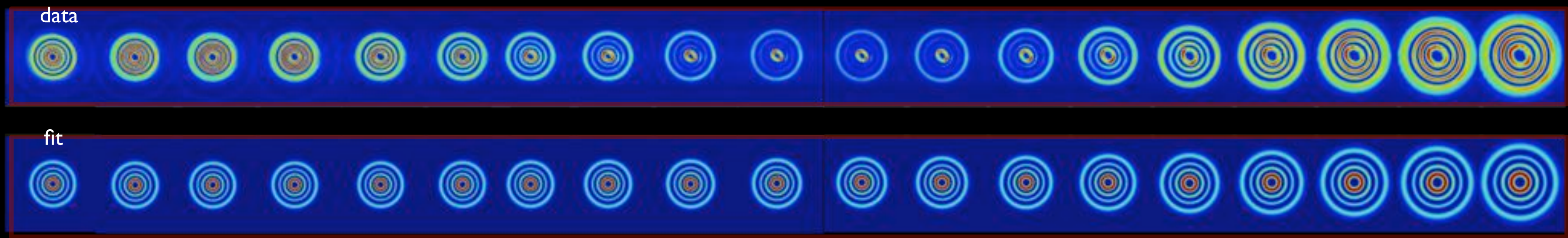




mode Matching

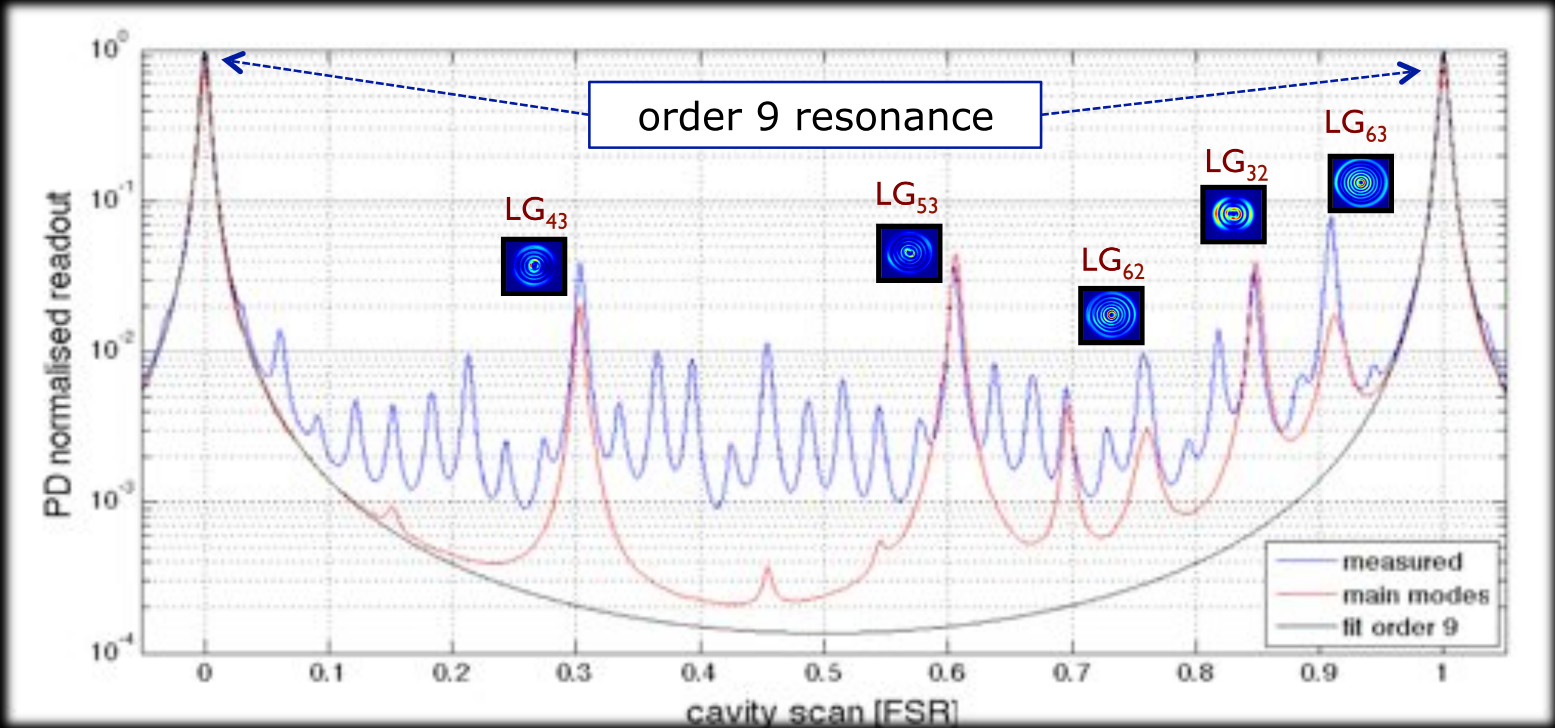
- Normal beam profiler won't work with higher-order modes
- Custom Matlab script to automatically find LG mode patterns in image, fit the target beam shape and derive beam spot radius
- Mode matching can be done with similar accuracy to LG_{00} modes but has to be done very carefully





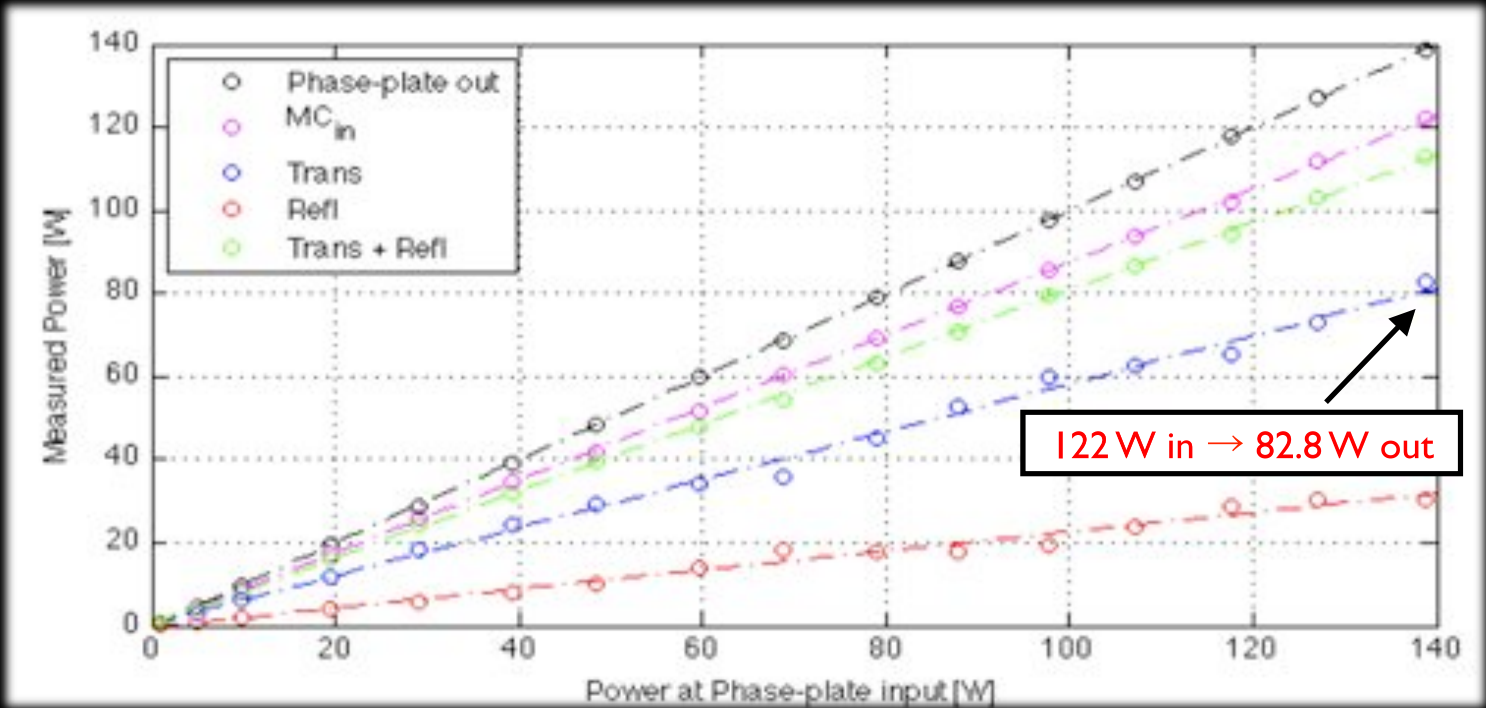
mode content analysis

- Use MC cavity scans to analyse mode content of phase-plate generated beam
  - Spurious LG beams easily identifiable with CCD images analysis, use modal fit of cavity scan to estimate mode content: get >75% of beam power in order 9 mode
  - Increase of about few % of the non order 9 content occasionally observed at higher power (currently under investigation)



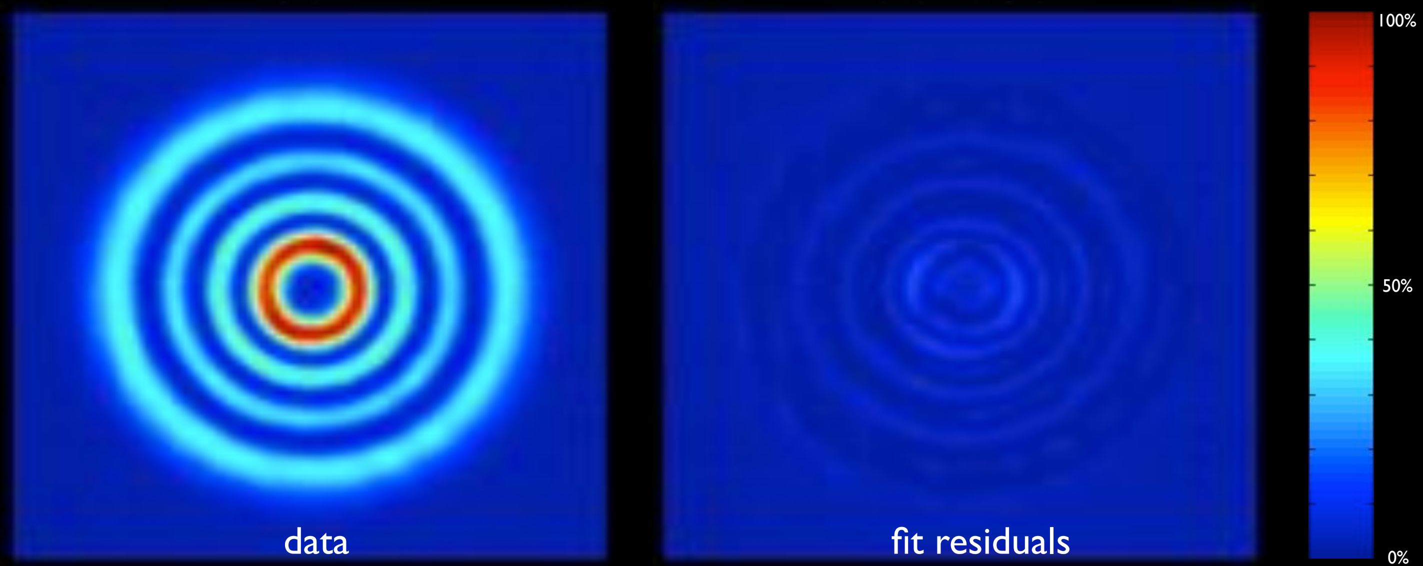
mode cleaning

- Lock MC to order 9 resonance to enhance LG_{33} beam purity by filtering out non order 9 modes
  - Lock up to full available power: system responds linearly to laser power
  - Observed some enhanced power fluctuations and beam pointing on the transmitted beam at high input laser power (currently under investigation)



mode cleaning

- Lock MC to order 9 resonance to enhance LG_{33} beam purity by filtering out non order 9 modes
  - No noticeable change in output beam as the input laser power increases
  - Best beam so far: >95% pure 82.8W LG33 beam



summarising

- LG modes interferometry proved feasible and compatible with current sensing and control techniques
    - Successful tests on table-top experiments, using mode conversion technology proved feasible and reliable
- Mode degeneracy causes contrast defects, mirror quality beyond state-of-the-art (Advanced Virgo/LIGO) is required
    - Analytical description of coupling could allow development of good enough mirror surface quality
- Test with suspended interferometers confirms complication when passing from table-top to large scale, but lots of expertise has been gained
- High-power stable LG beam has been successfully demonstrated with 95% purity up to 82.8W

strategies for the future

- LG modes matured from basic idea to established technology
- Experience with prototypes show that:
  - LG modes aren't plug'n'play: implementing LG interferometry in pre-existing apparatuses more complex than thought, expertise not mature yet for short-term, optimal design is needed
  - LG modes results are still encouraging
- Mode degeneracy problem still unsolved, further investigations ongoing
- LG modes are difficult but not impossible, still a valid candidate for mirror thermal noise mitigation for future GW detectors

- end… thanx for listening!