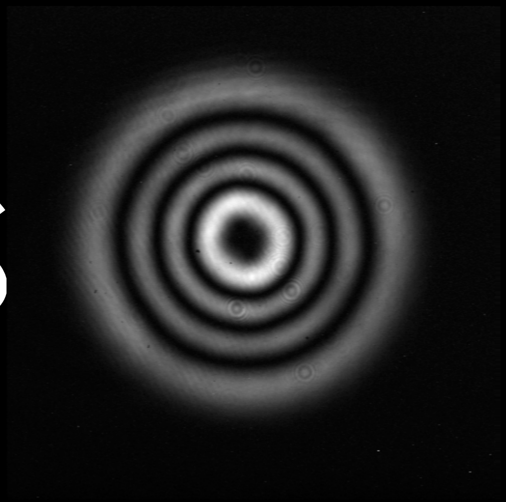
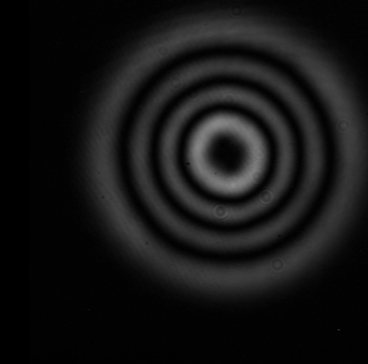
LAGUERRE GAUSS MODES



Andreas Freise 14.05.2012 GWADW Hawaii

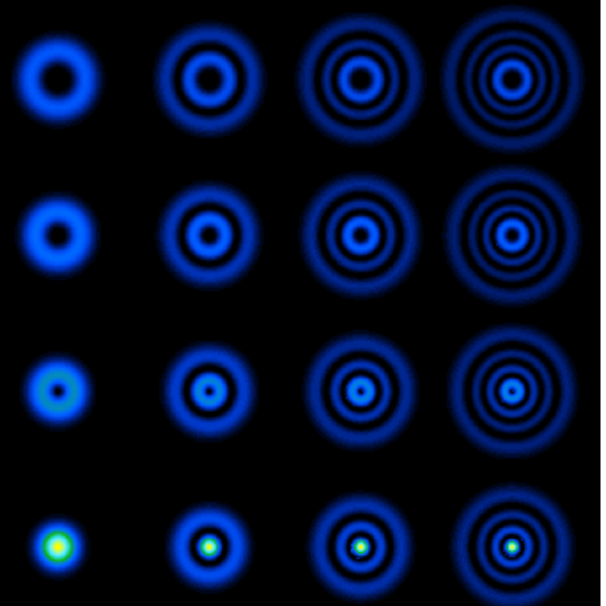
Overview

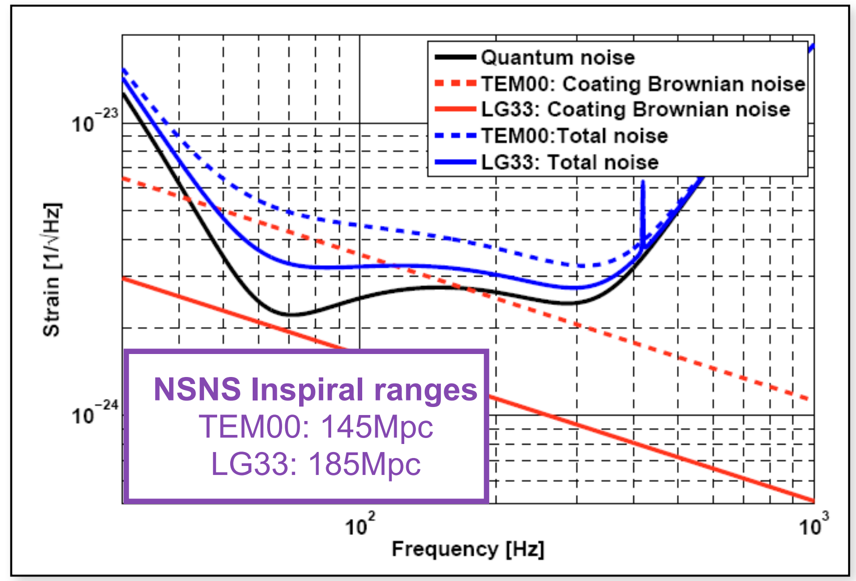


- Laguerre-Gauss modes for GW detectors
- Preliminary results: Experimental test at the Glasgow 10m prototype
- Preliminary results: Experimental test at the Hannover high-power laser system

Thermal noise reduction

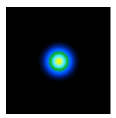
- Higher-order Laguerre-Gauss modes can reduce the thermal noise (bulk, coating)
- Technique promises to be compatible with other implemented and planned optical technologies

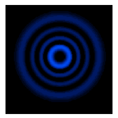




Chelkowski et al. PRD 79 (2009) 122002

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

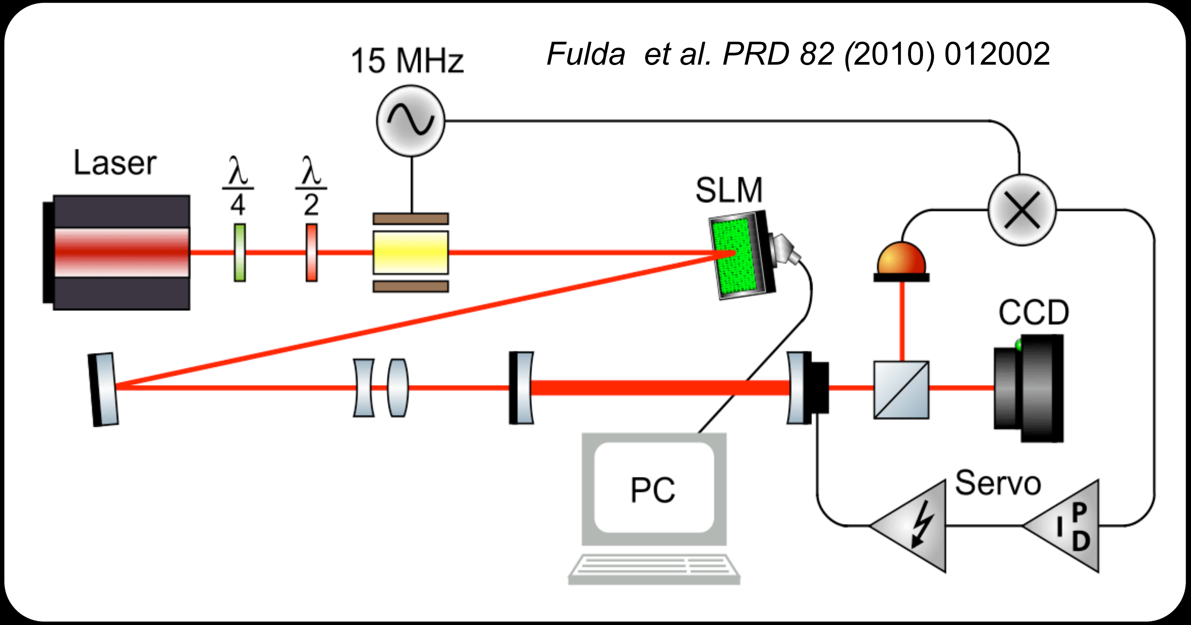
Improvement in h(t)

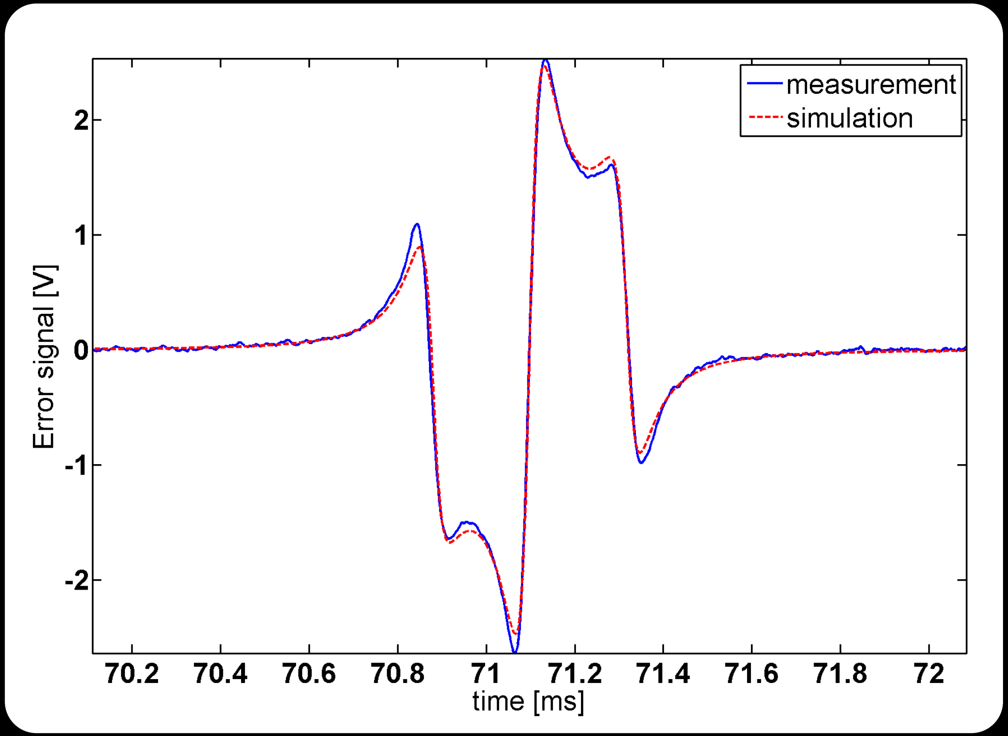
$$h_{33} = \frac{h_{00}}{2.7}$$

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

Sensing and Control

- Simulation of length and alignment signals for simple cavity and Michelson interferometer predicted no difference between LG00 and LG33 beams
- First experimental demonstration of LG33 interferometry: locked LG33 beam to a linear pre-modecleaner with Pound-Drever Hall, achieved stable LG33 beam with >99% purity.
- Independent effort on mode cleaner and Michelson table-top demonstration by Granata et al. 2010
- Conclusion: error signals are effectively identical! Standard control systems work without





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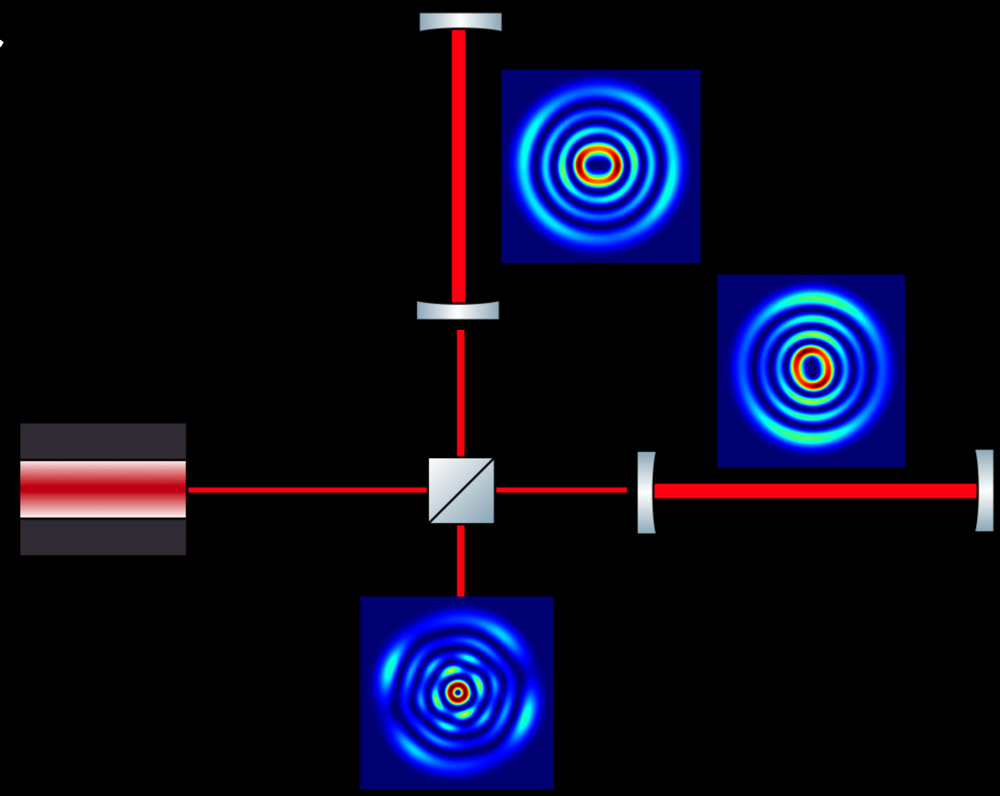
Mode degeneracy

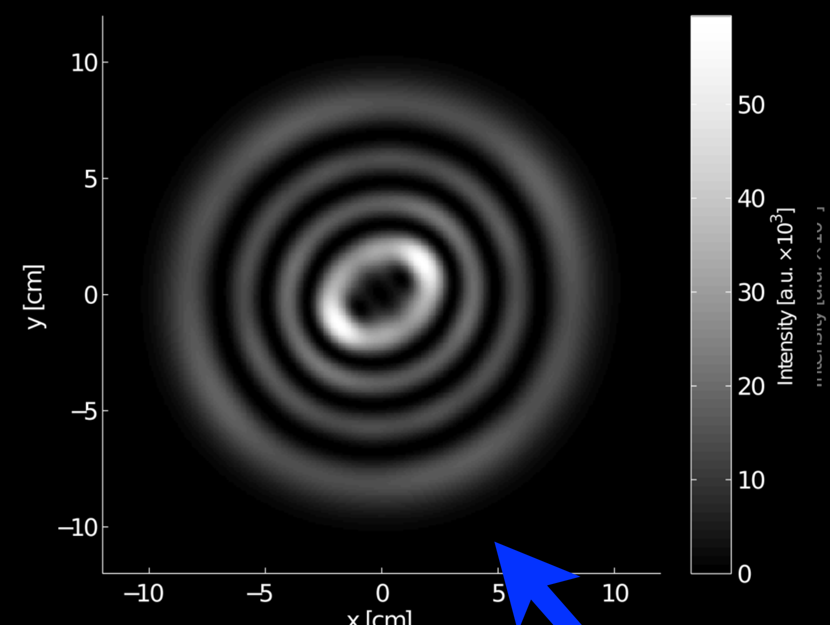
- The problem with any higher order mode is: any cavity resonant for the selected mode will be also resonant for others of the same order
- A cavity pumped with a beam in a cavity-eigenmode will typically run in that mode
- However small defects in the mirror cause coupling into unwanted modes
- Even if resulting beam shapes are stable the resulting contrast defect reduces the sensitivity

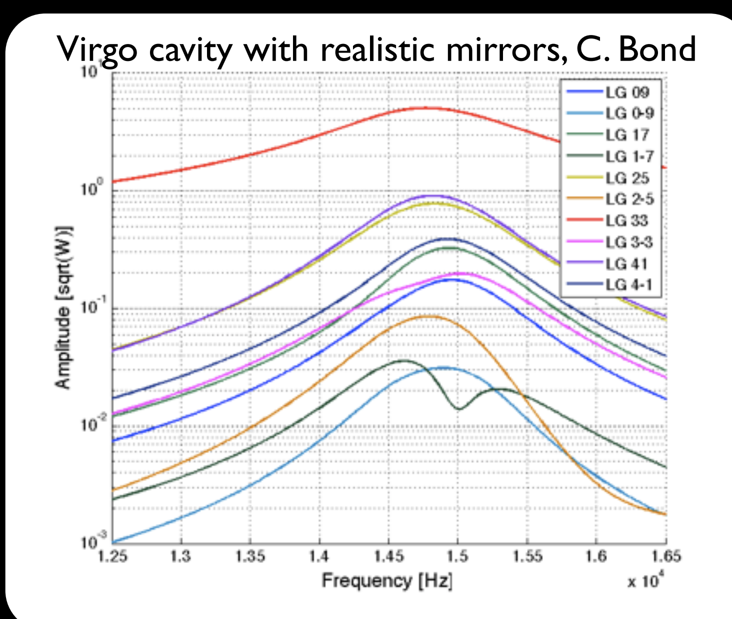


Helical LG modes of order 9

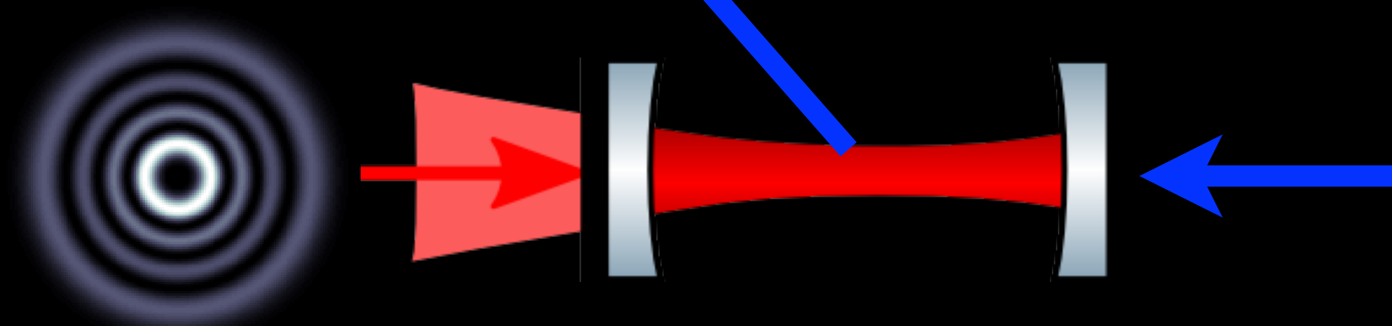
Beam distortion

- Applying realistic mirror surfaces (Advanced Virgo / aLIGO mirror maps) in numerical models show distorted beams
- 3 independent research efforts, two using a statistical approach and FFT simulations (Galimberti et al, Hong et al), and one using modes and Zernike polynomials (Bond et al)
- Resulting contrast defect at beam splitter too large with current surface quality

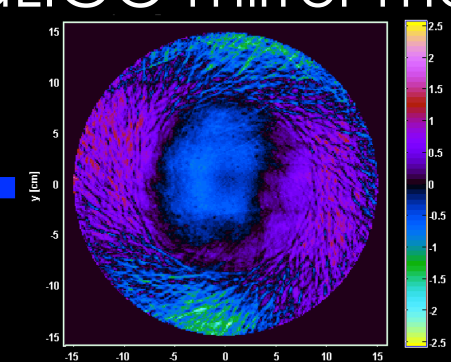




LG33



aLIGO mirror map



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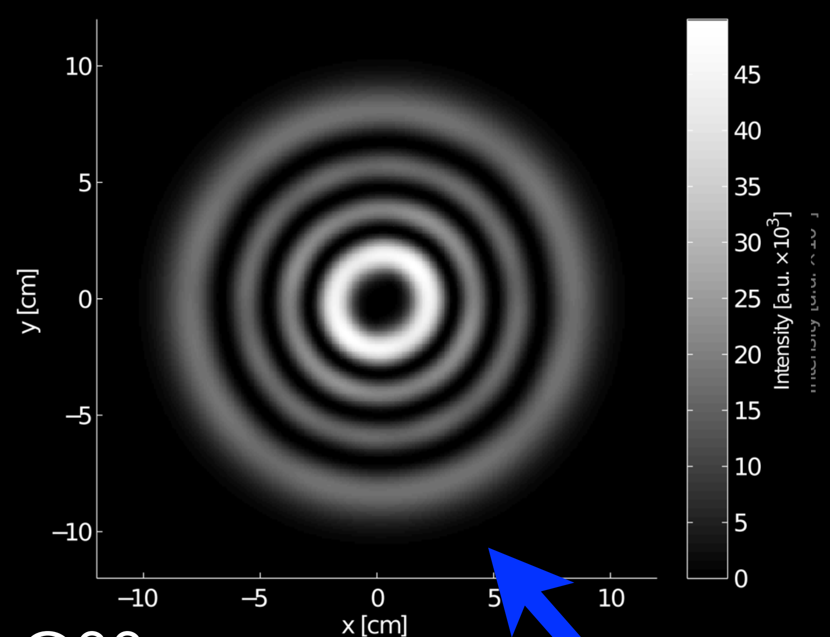
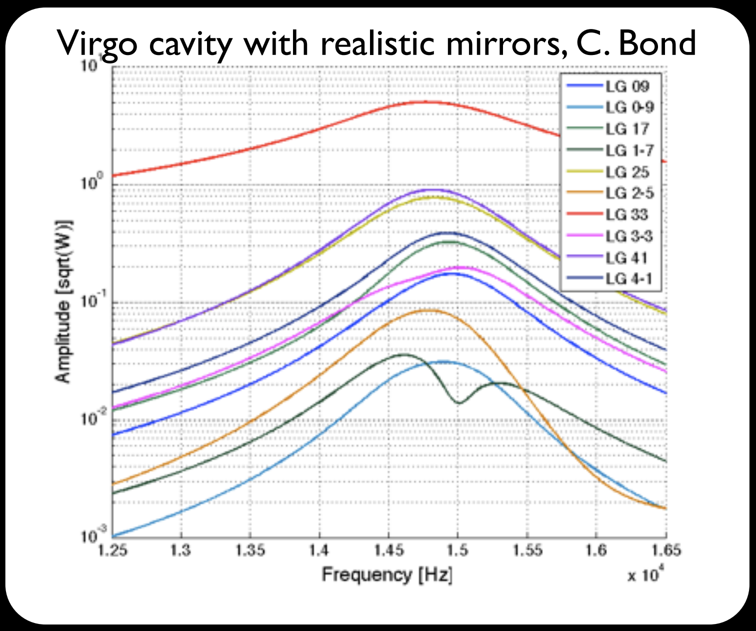
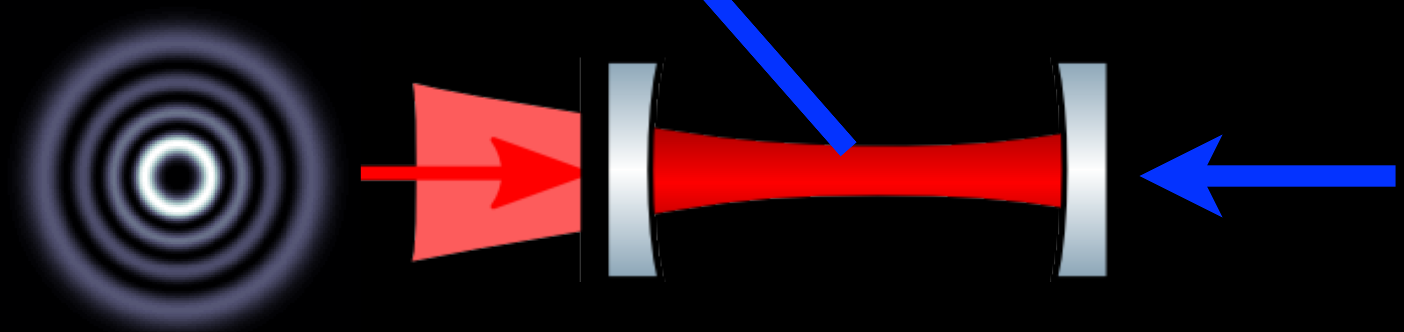
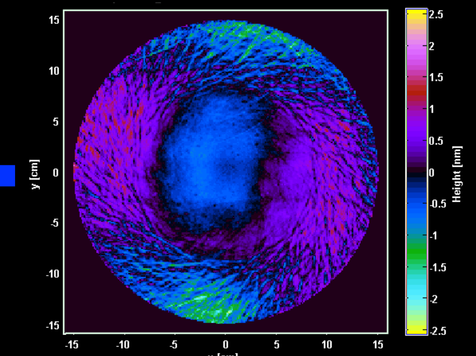




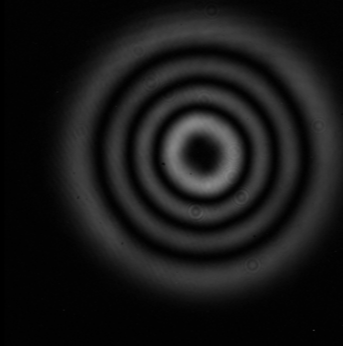
LG33



aLIGO mirror map



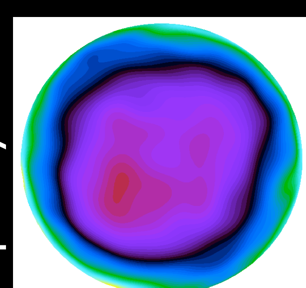
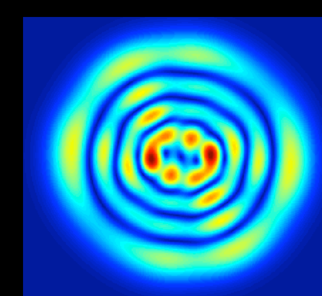
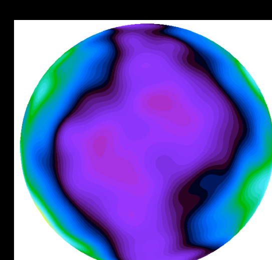
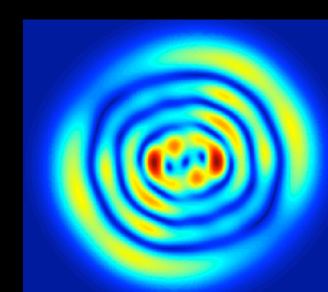
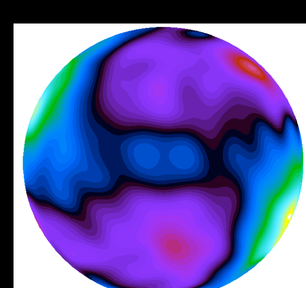
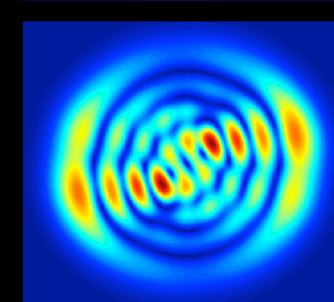
Mirror surface



- A detailed analysis using Zernike polynomials show that the worst coupling results from specific distortions at large spatial wavelength, strongly dominated by astigmatism

- We have developed an analytic framework describing this coupling, Bond et al. Phys. Rev. D, 2011, 84, 102002

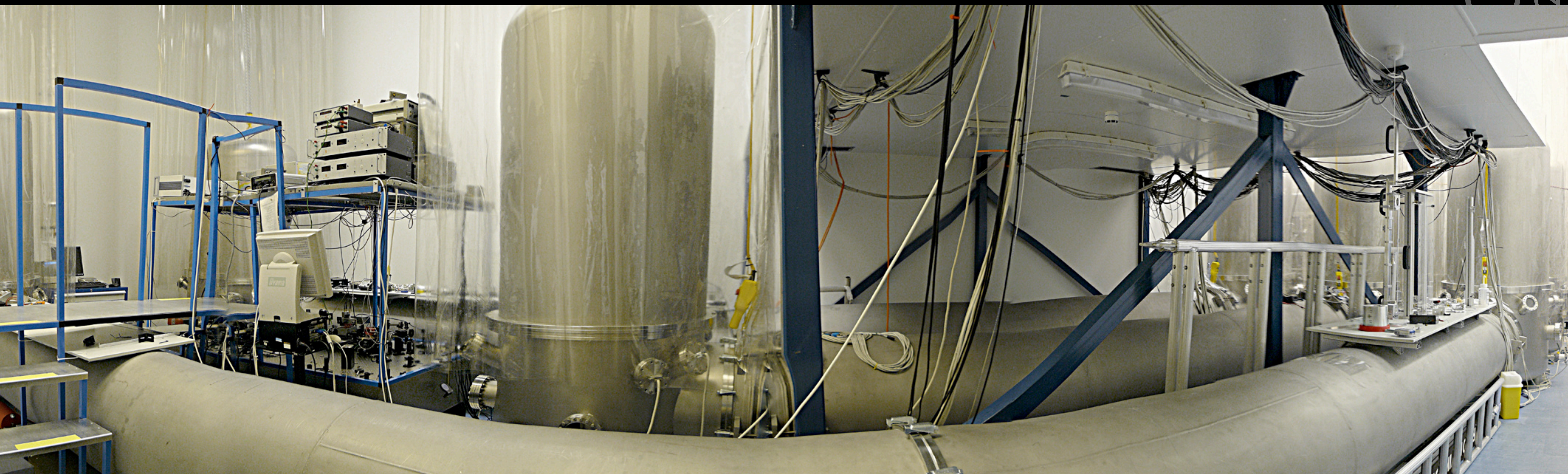
all mirrors have the same spatial frequency content

	MIRROR	Z2±2 content	Z20 content	Circulating beam	LG33 mode content [%]
BEST		0.49	0.51		78.54
AVERAGE		0.48	0.52		69.94
WORST		0.856	0.144		52.35

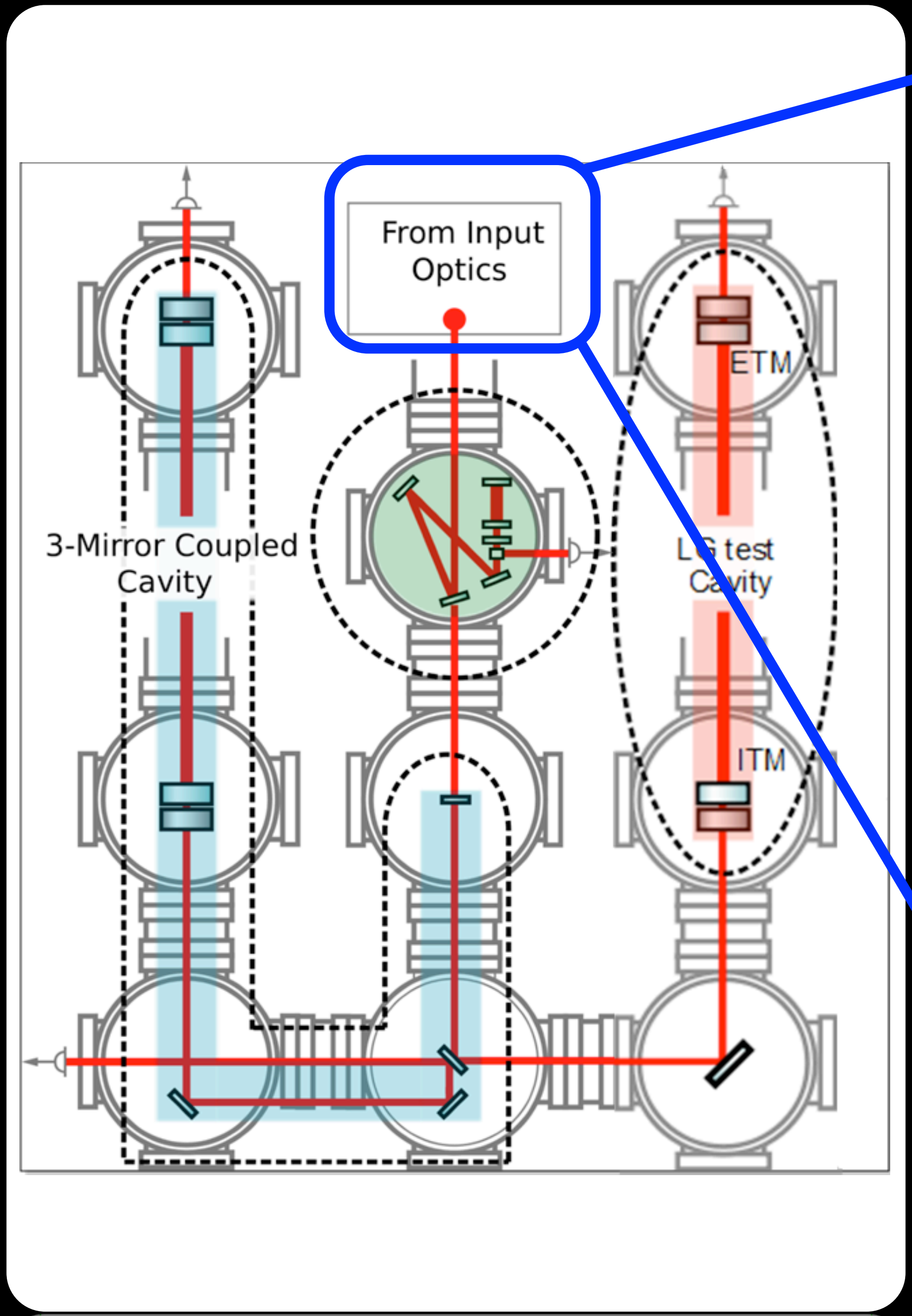
Glasgow10m prototype

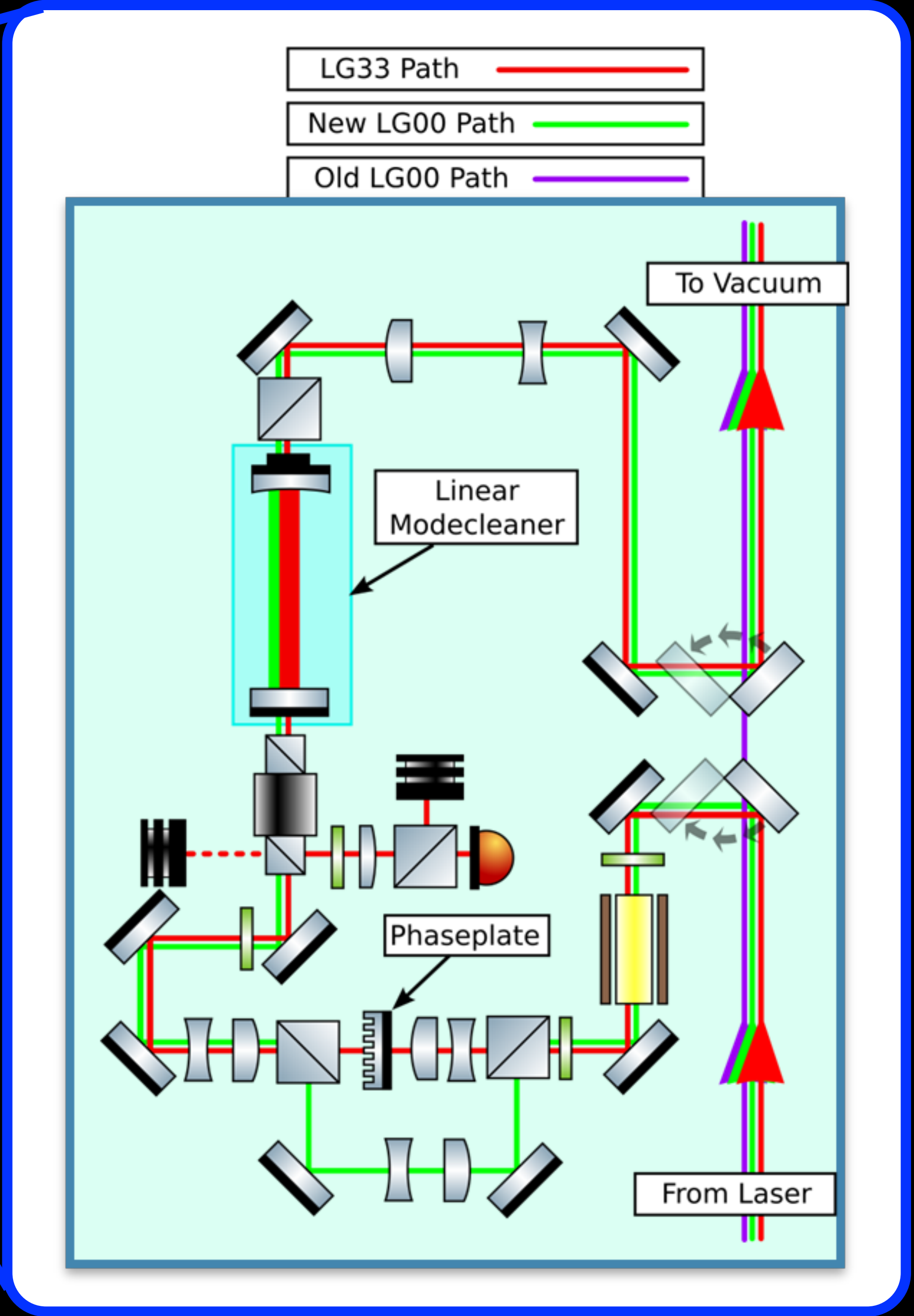
- Test of LG33 mode at the 10m prototype with suspended optics and full control
- Compare experiment with simulations, especially regarding mode distortion and coupling

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



Optical Layout





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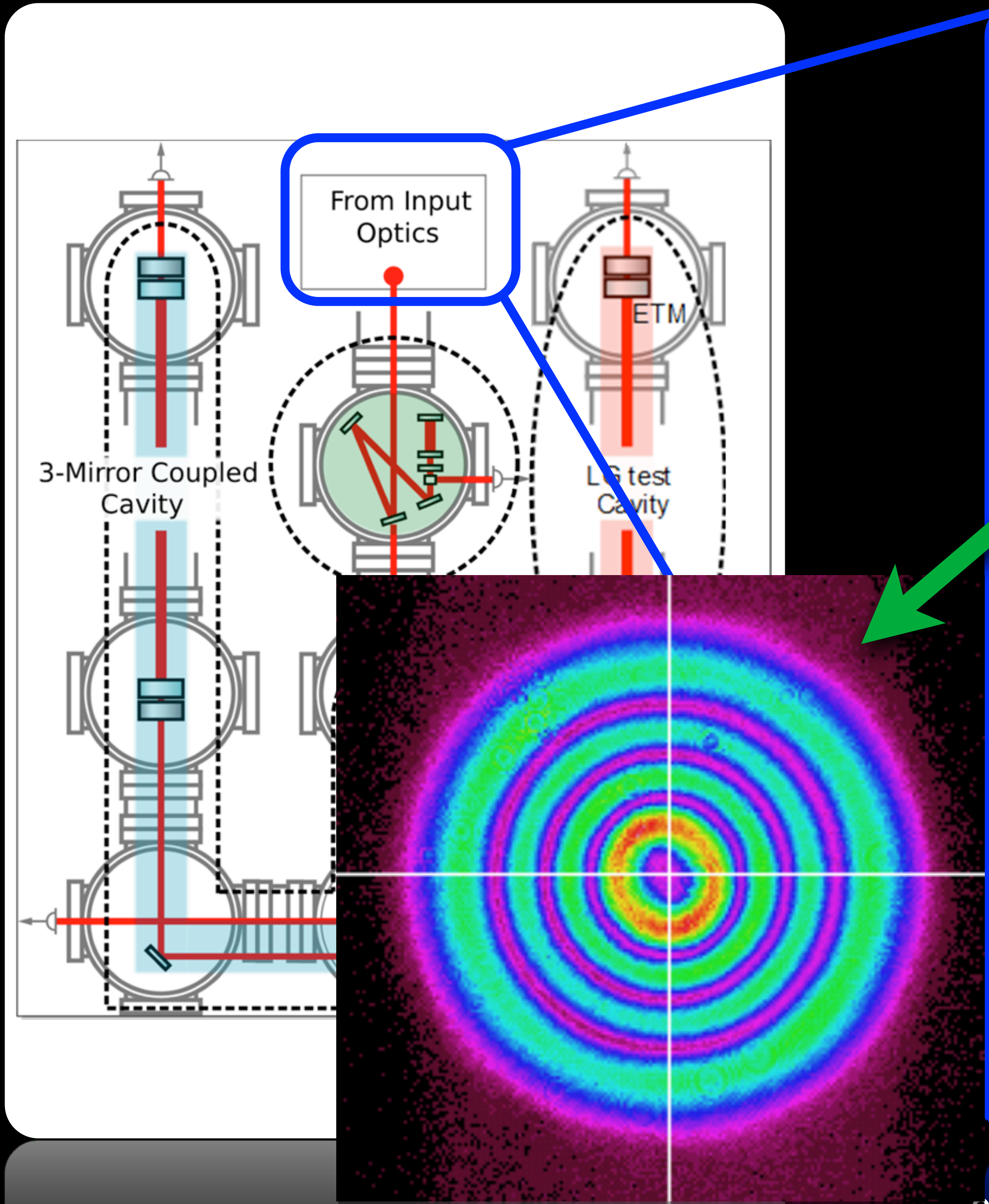
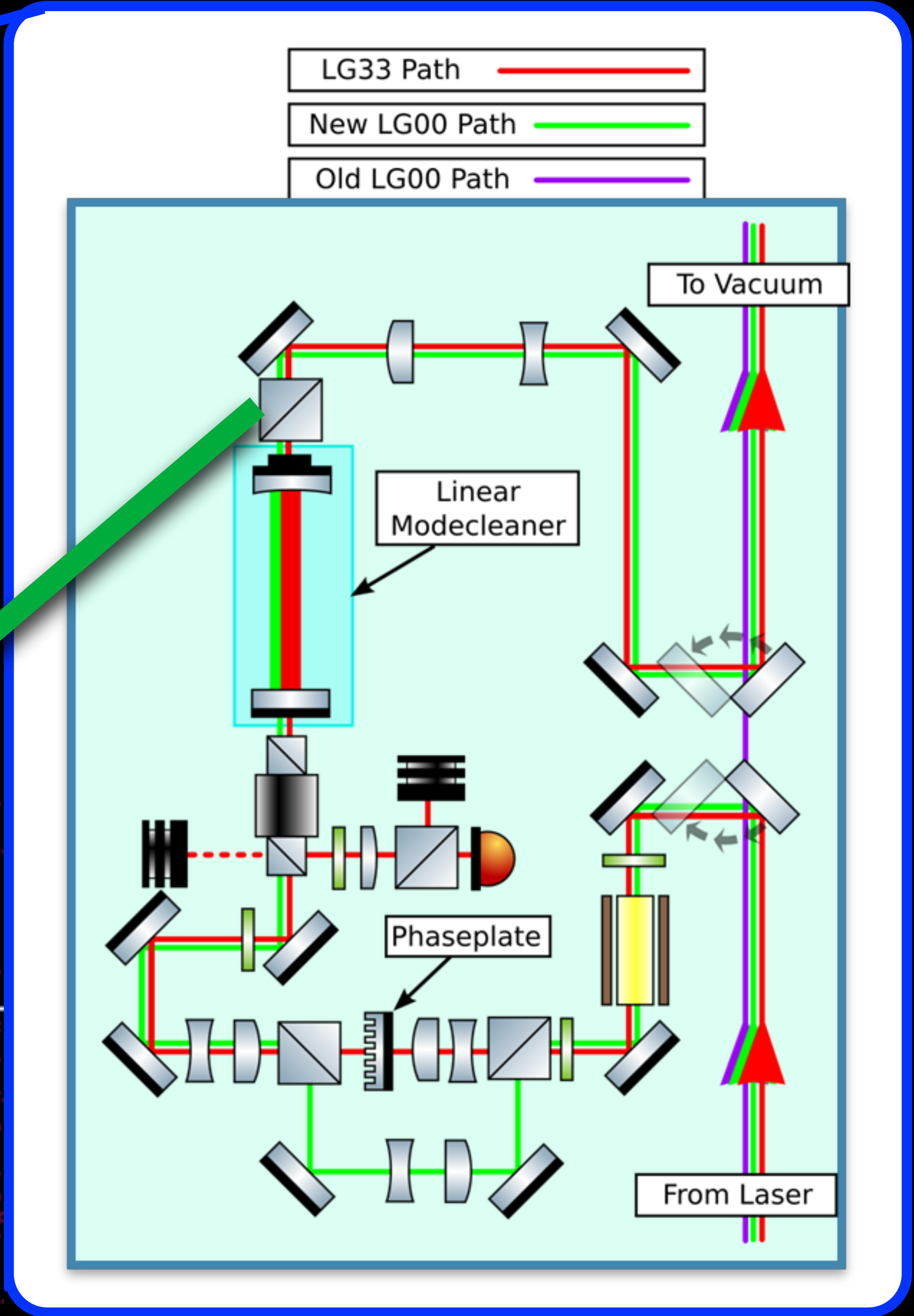
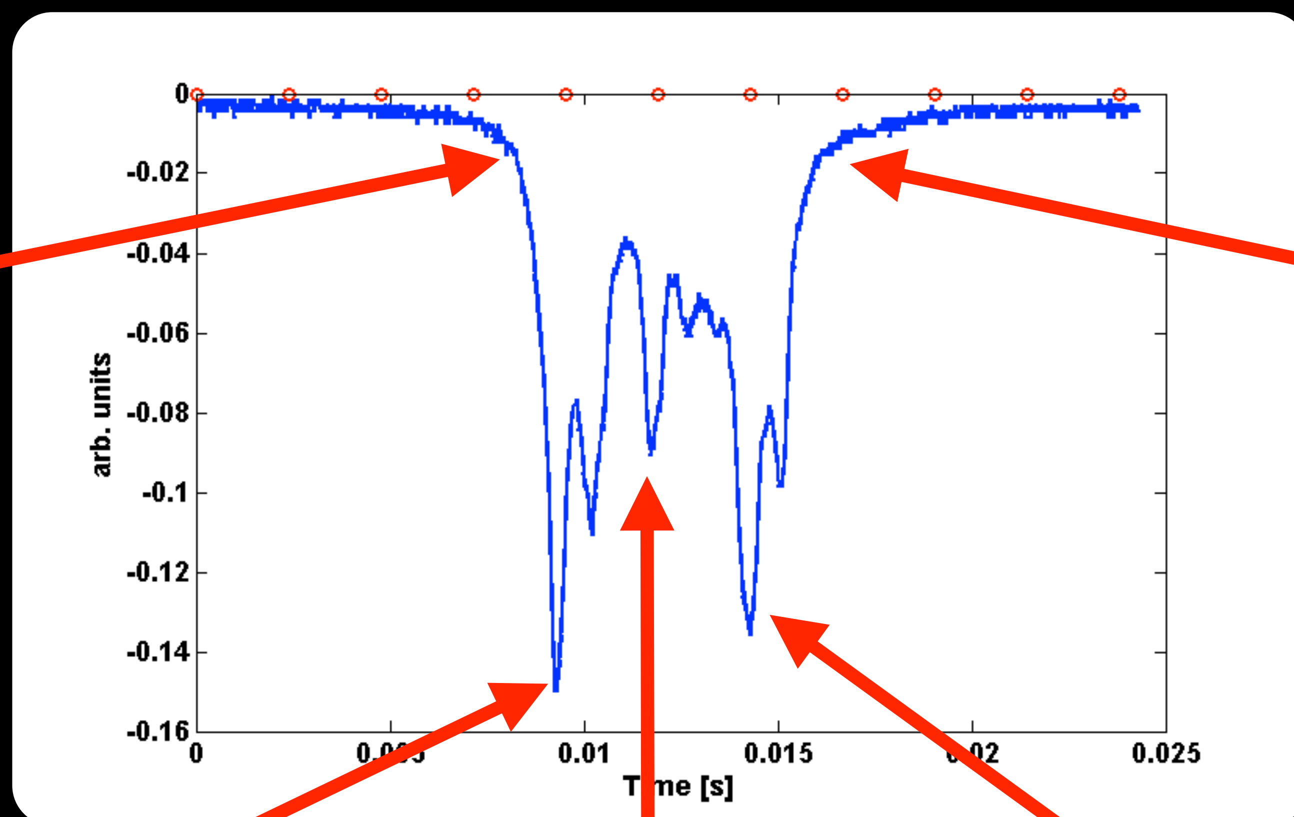
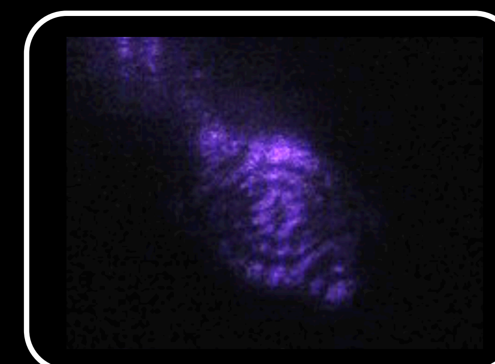
Optical Layout

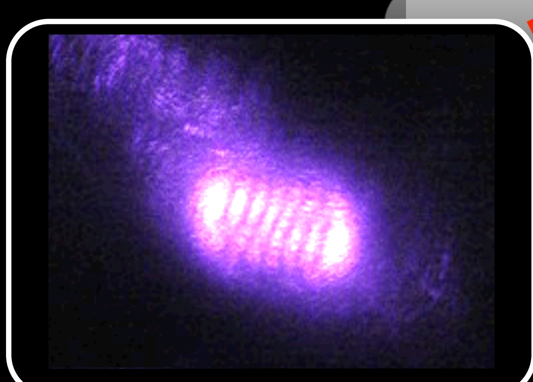


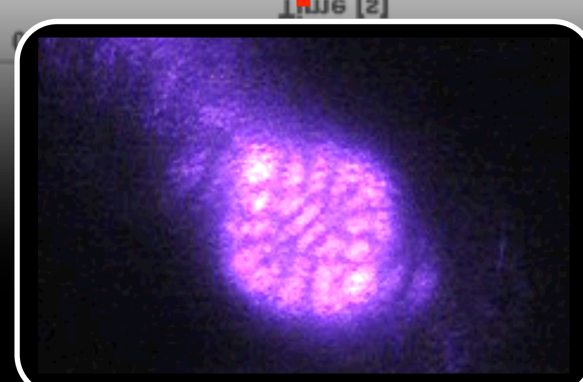


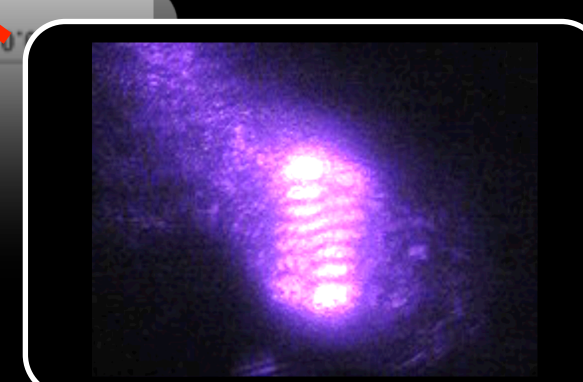
Scanning the cavity











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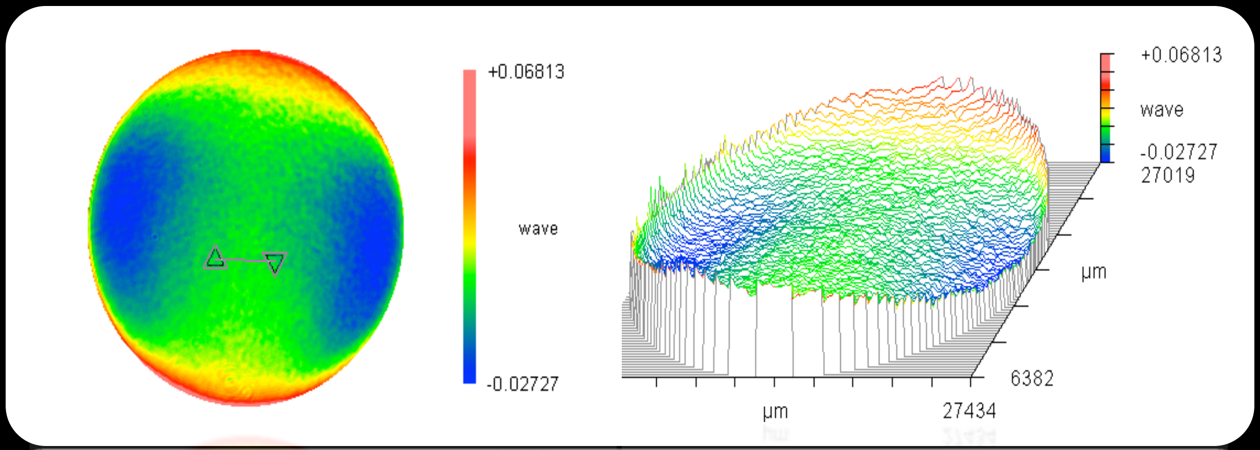
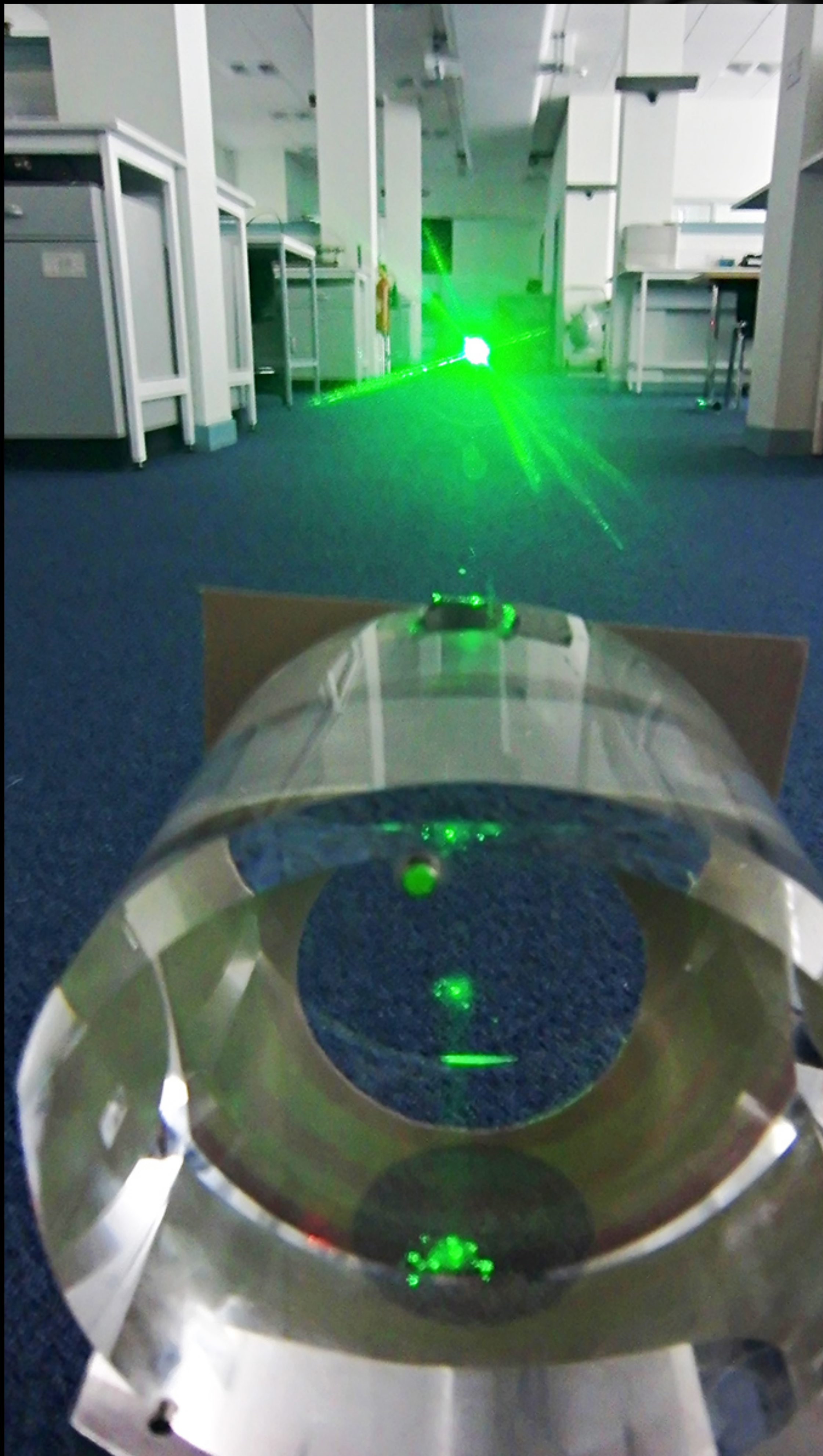
Cavity mirrors

- Not enough data about the cavity mirrors
- Extensive measurement campaign to determine mirror surface characteristics
- Wyko, Zygo, Ronchi method, Foucault method, ...



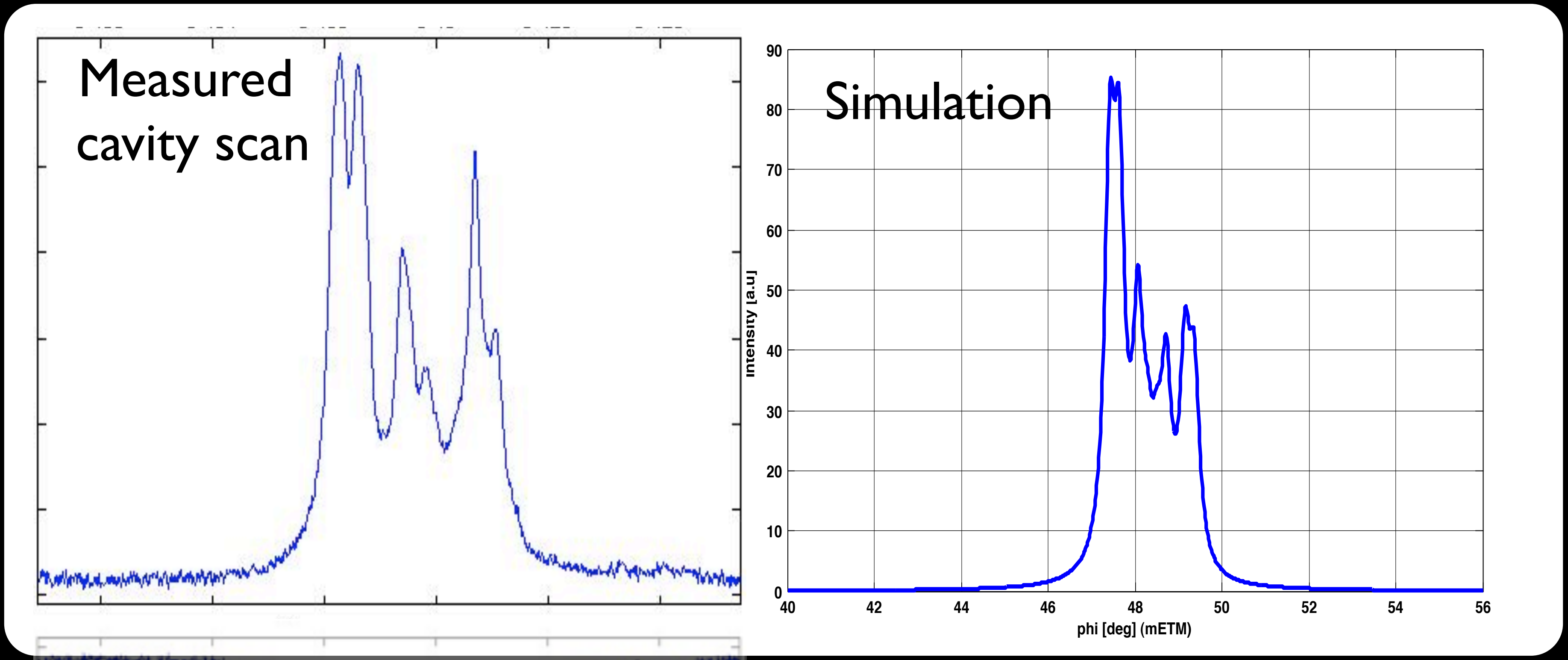


Simulation vs. Experiment

- Preliminary: Using measured surface maps for ITM and measured astigmatism for ETM gives a good match between simulation and experiment.

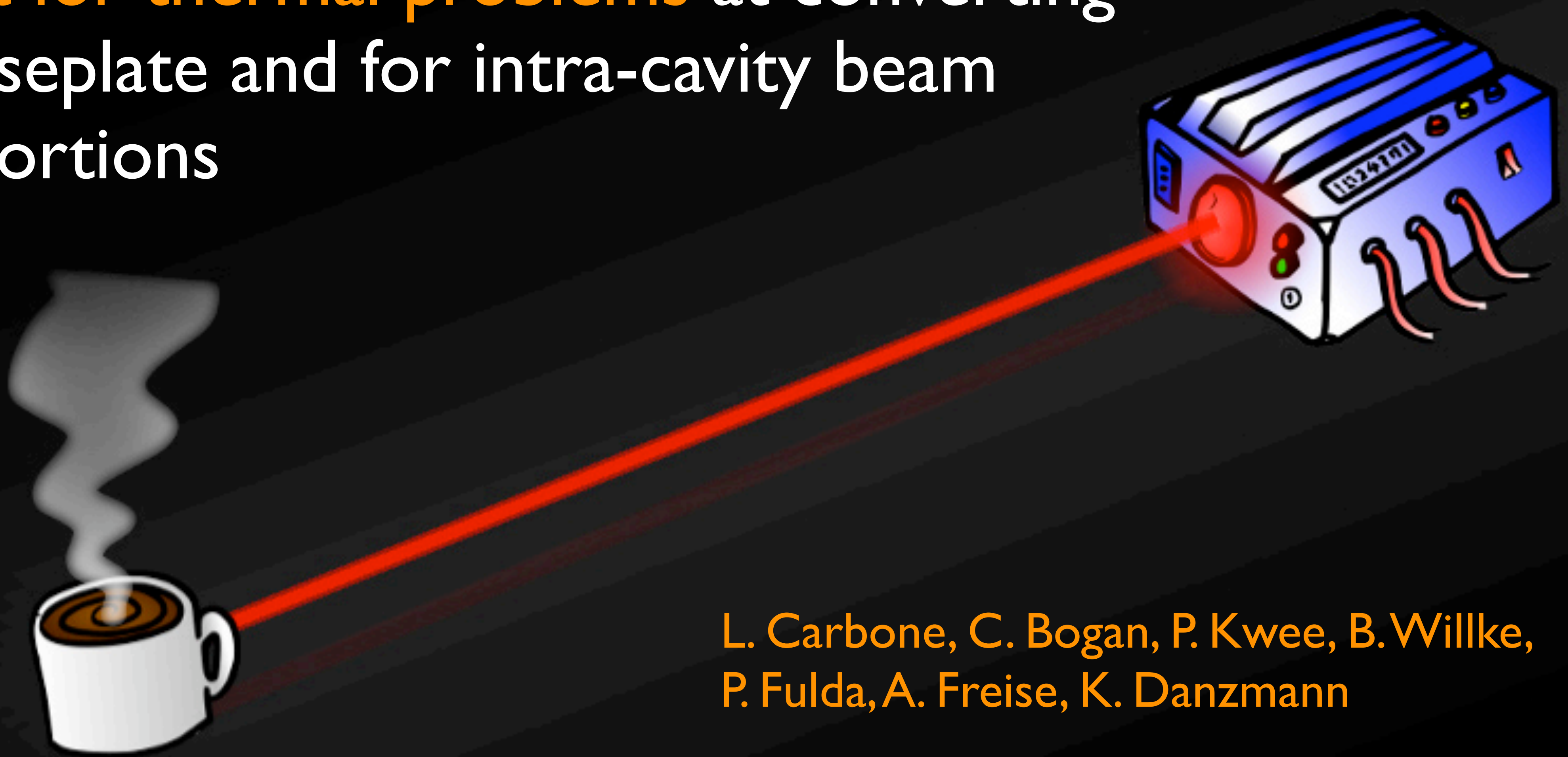
- Mirror data: ETM RCx=15.26m, RCy=15.2m,
  ITM RCx=7080m, RCy=-2200m

- Conclusion: Astigmatism breaks the cylindrical symmetry required for LG modes, experimental result fully understood once mirror surface information is available



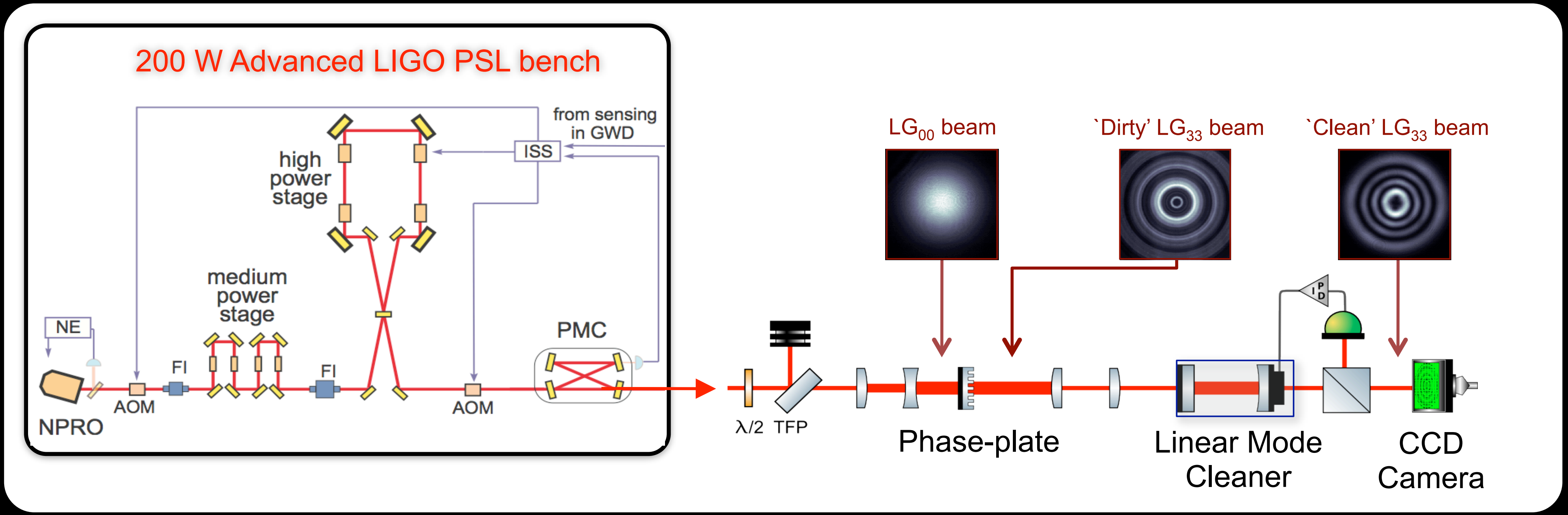
Hannover high-power laser

- Integrating LG33 generation into an aLIGO-like laser at the AEI Hannover
- Experimental demonstration of high-power LG33 beam
- Test for thermal problems at converting phaseplate and for intra-cavity beam distortions



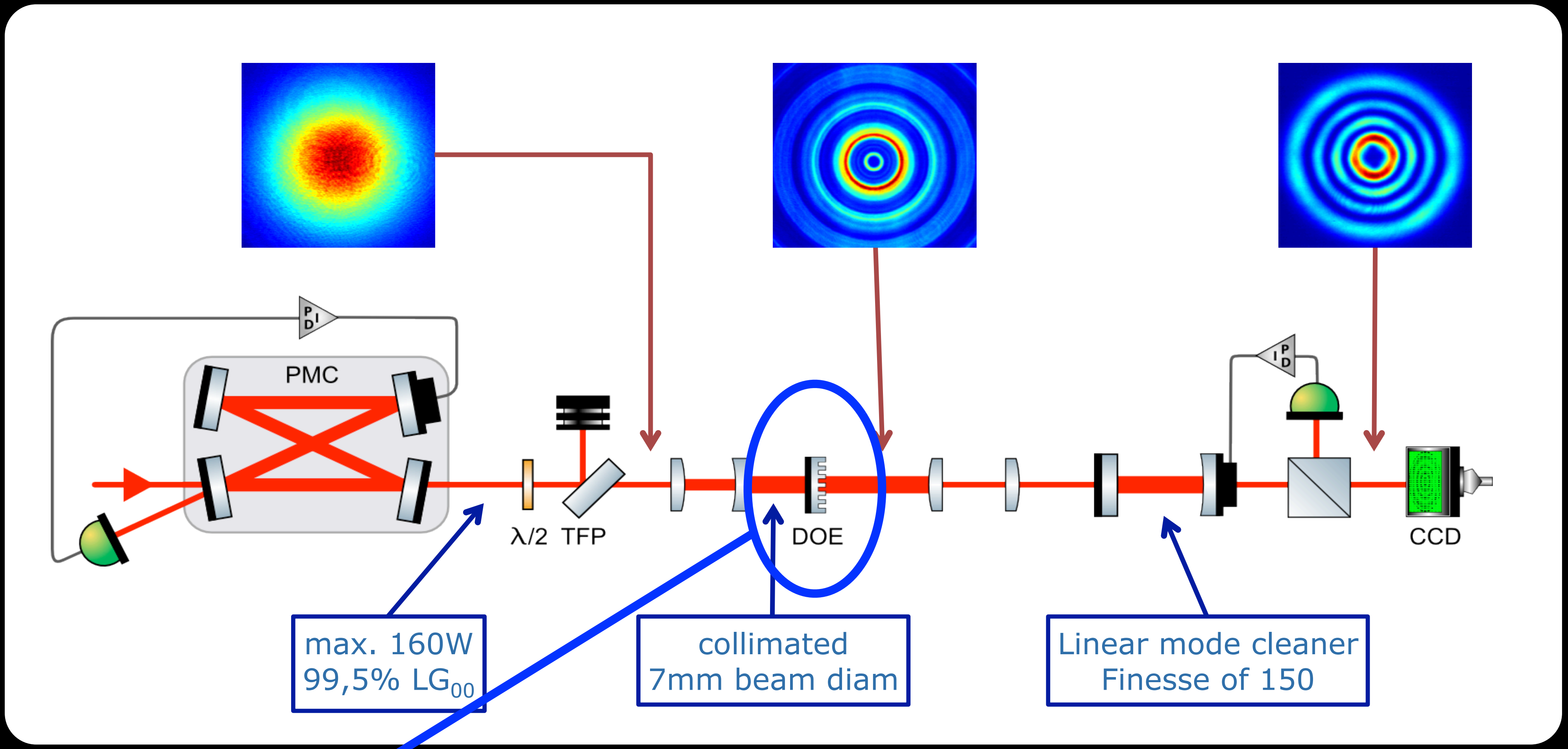
L. Carbone, C. Bogan, P. Kwee, B. Willke, P. Fulda, A. Freise, K. Danzmann

Optical layout 1



- Use the aLIGO 200W laser as input to our standard LG33 conversion setup: phaseplate + pre-modecleaner
- Laser output can be tuned for testing mode conversion for different powers

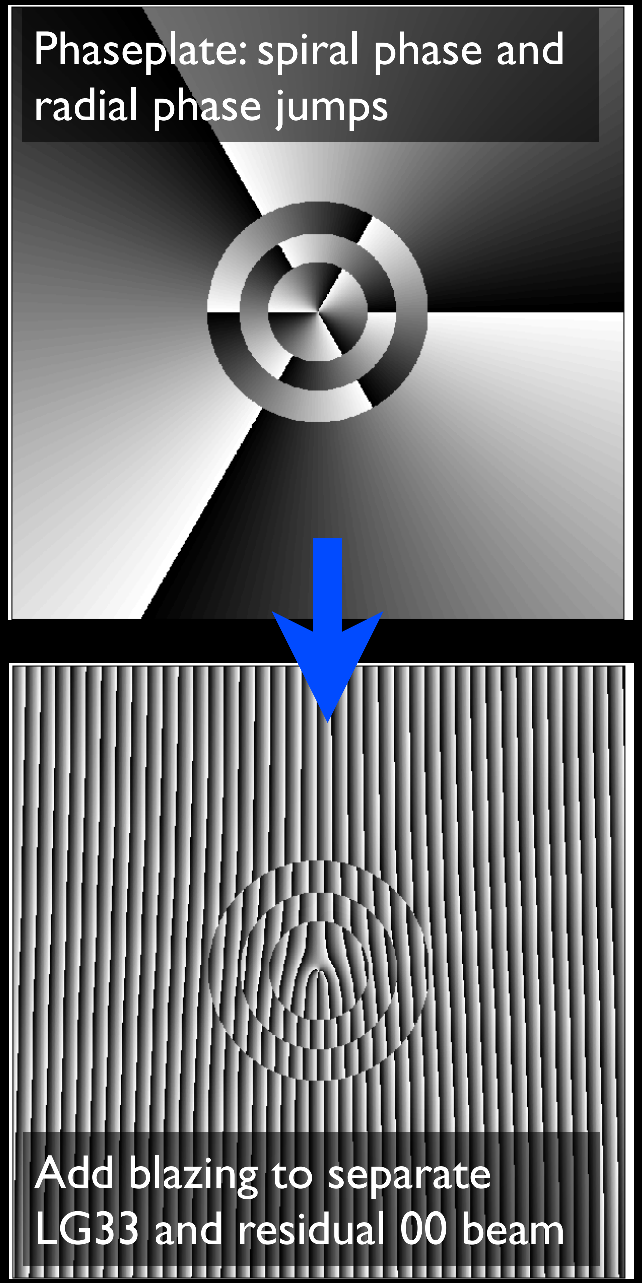
Optical Layout 2



Conversion happens at the `phase plate'

Phase plate

- Fused silica etched diffractive phase-plate, 3000×3000 pixels, 7×7um^2 size, 8 bit phase modulation, 1064nm AR coating on both sides
- Nominal LG_{33} conversion efficiency > 74 %
- >95% of input power in main diffraction order
- ≈ 4% in other diffraction orders, <0.2% reflected



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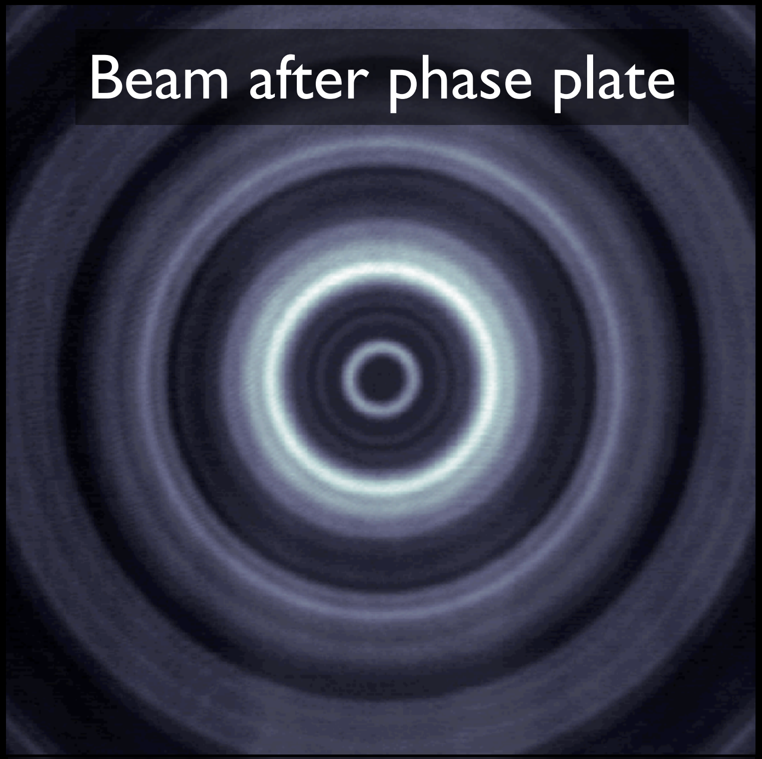
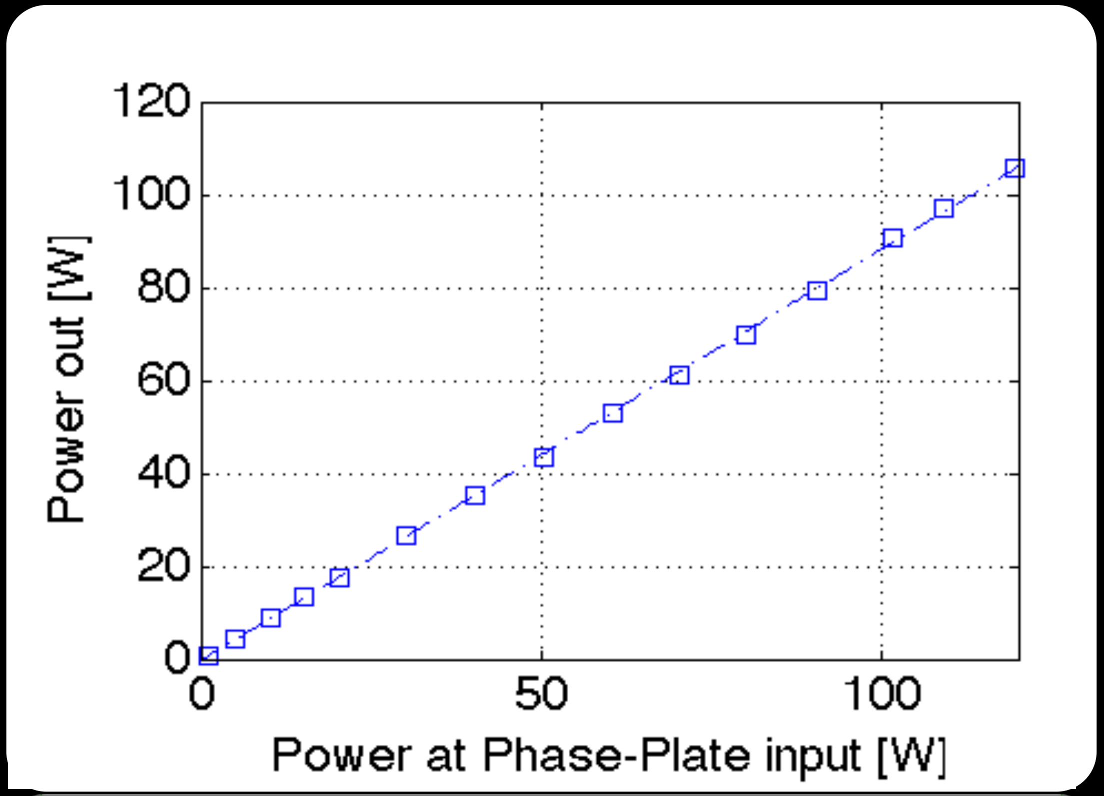
High-power conversion

- Direct measurement of converted beam at the phase plate
- Stable conversion up to maximum available incident power of 120W
- Linear response and no degrading of phase plate with higher power

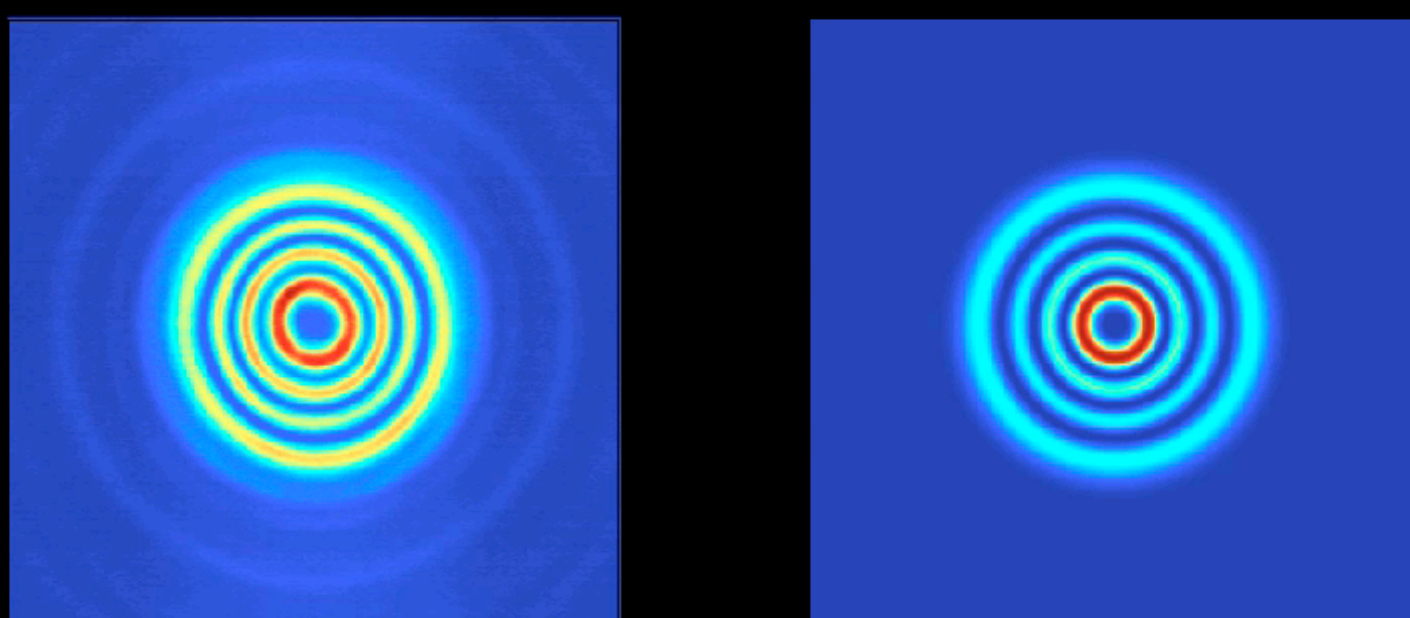




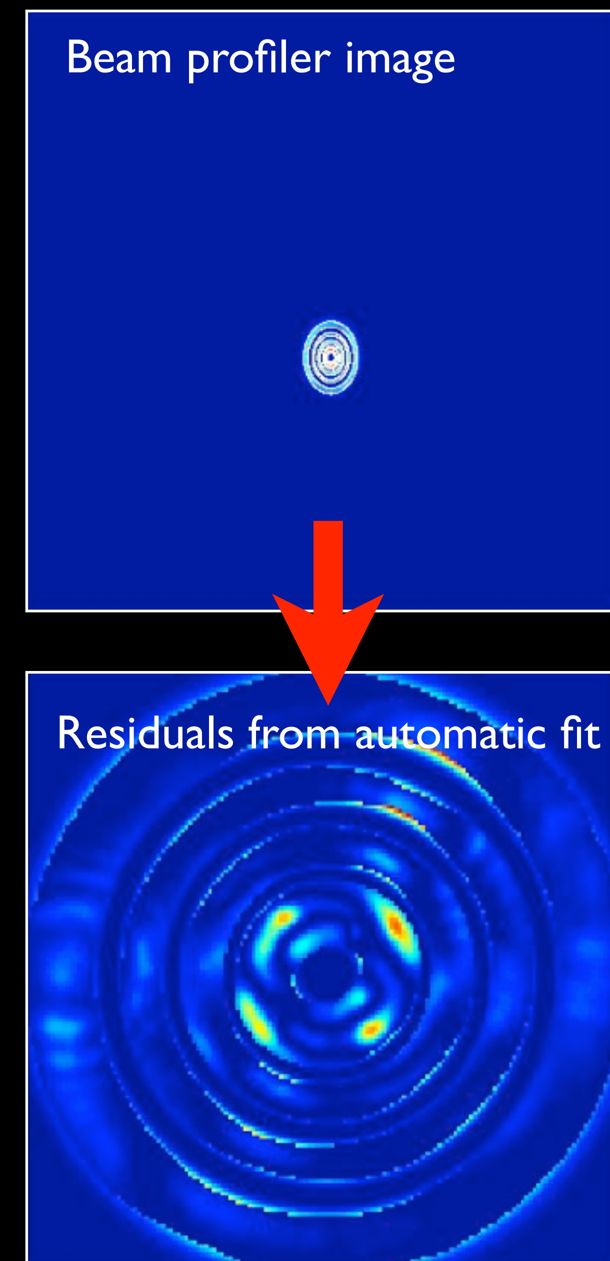
Mode matching

- Mode matching has to be done very carefully
- 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

measured data | fit result

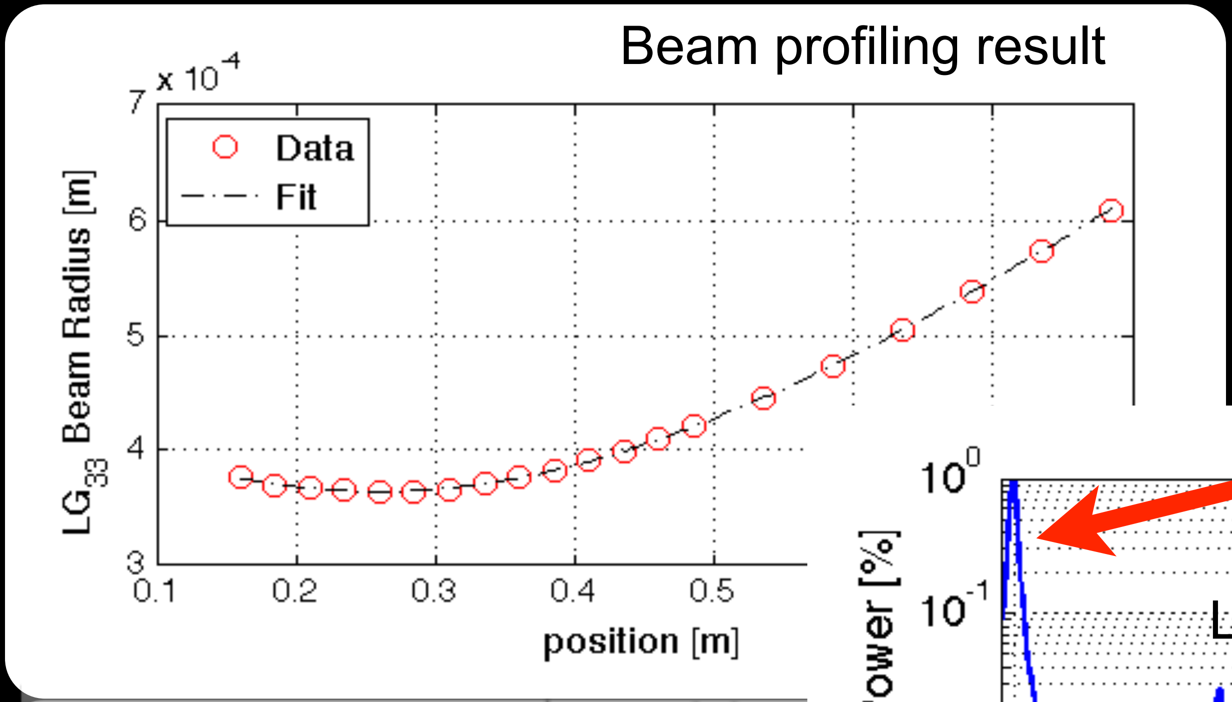


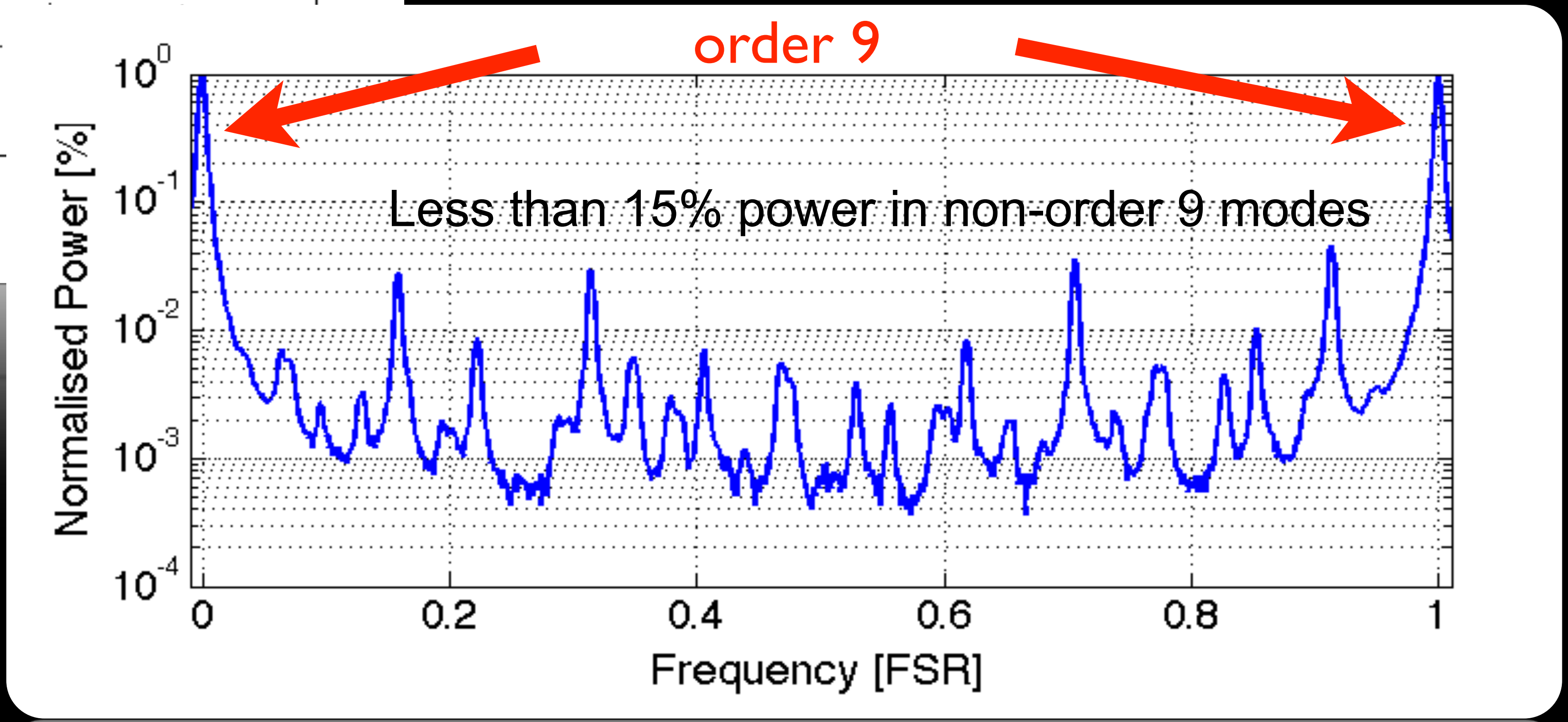
z = 185 mm | z = 185 mm



Modecleaner scan

- Pre-modecleaner: 210mm long, flat-curved mirror cavity on Al spacer currently using (glued) BK7 mirrors,Finesse = 150, dithering lock at 1.5 MHz
- Stable lock until 43W input power, limited by thermal lens developing in BK7 mirrors





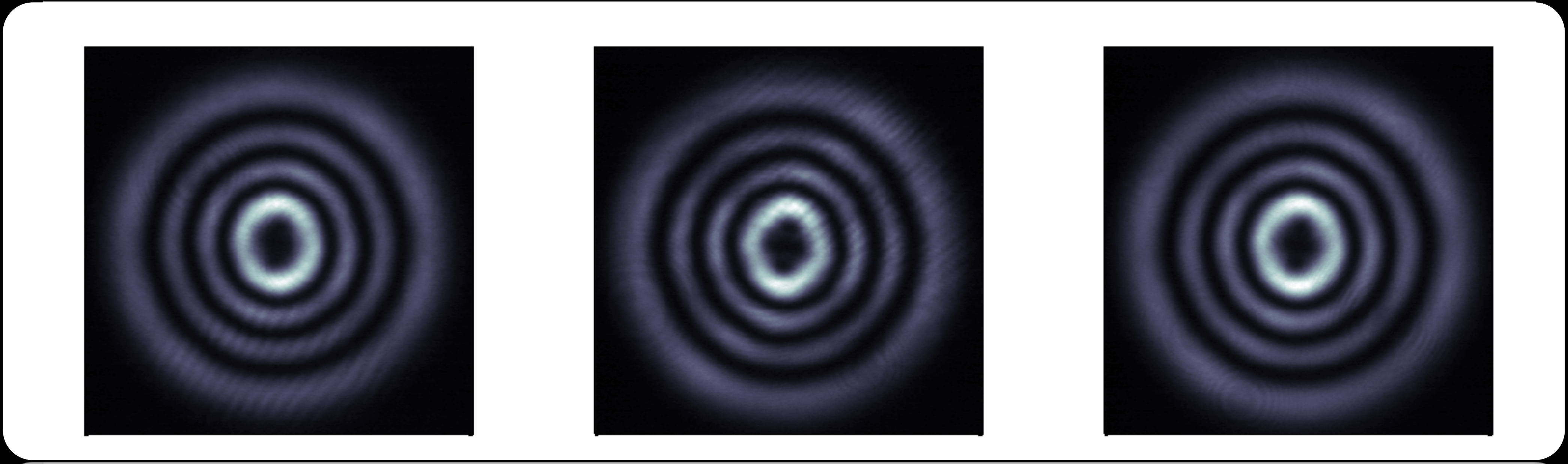
Beam quality

- Beam quality after pre-modecleaner >95%
- mostly unaffected by beam power

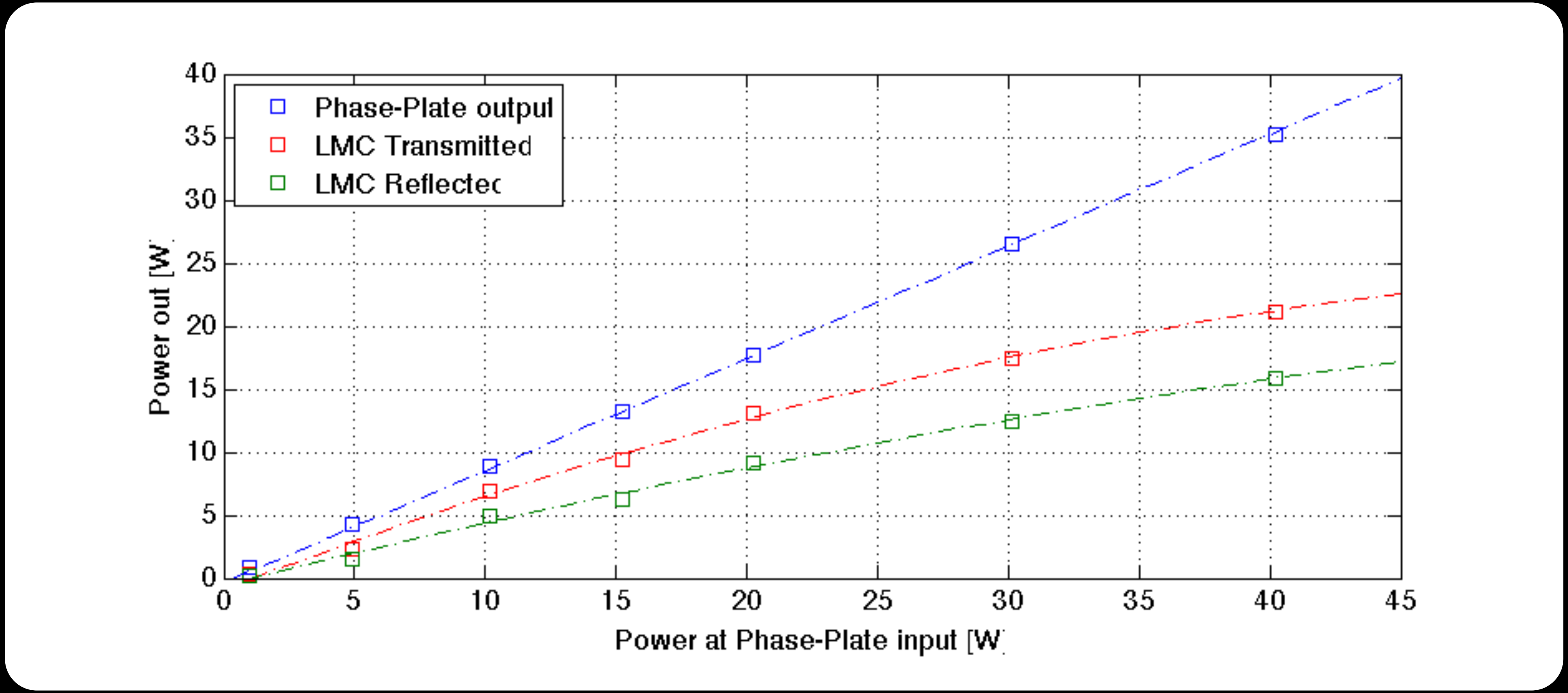
1W phase plate
1W mode cleaner

41W phase plate
41W mode cleaner

106W phase plate
1W mode cleaner



Mode cleaner output



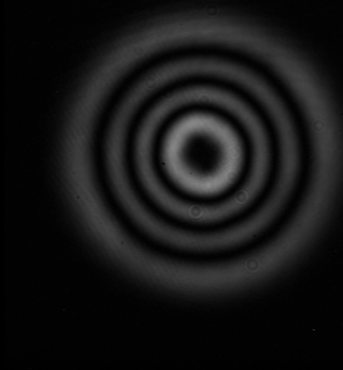
Conclusion:

- Successfully converted 120W LG_{00} beam into 106W higher-order LG mode beam, >85% power in order 9
- Successfully generated 21W LG_{33} beam, purity >95% (need to replace BK7 mirrors of the mode cleaner for higher power)

Conclusions

- LG modes are compatible with current sensing and control systems
- Successful experimental tests with table-top systems
- Mode degeneracy causes contrast defects, required mirror quality beyond state-of-the-art (Advanced Virgo/LIGO)
- Need new mirrors for prototype experiments, analytical description of coupling could allow development of good enough mirror surface quality
- High-power, stable LG beam has been demonstrated with 95% purity

Several of these slides were provided by:
Paul Fulda, Charlotte Bond and Ludovico Carbone



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