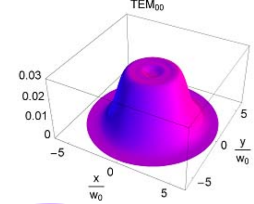
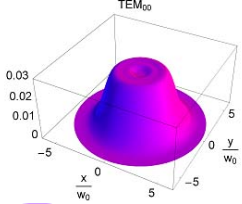


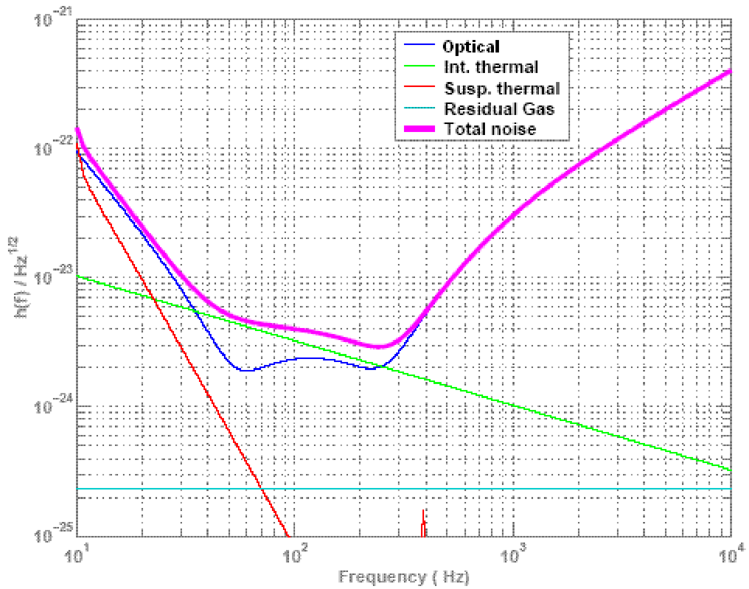
The Mesa Beam

Juri Agresti[1,2], Erika D’Ambrosio[1], Riccardo DeSalvo[1], Danièle Forest[3], Patrick Ganau[3], Bernard Lagrange[3], Jean-Marie Mackowski[3], Christophe Michel[3], John Miller[1,4], Jean-Luc Montorio[3], Nazario Morgado[3], Laurent Pinard[3], Alban Remillieux[3], Barbara Simoni[1,2], Marco Tarallo[1,2], Phil Willems[1]

1. Caltech/ LIGO
2. Universita’ di Pisa
3. LMA Lyon/ EGO
4. University of Glasgow

Why mesa beams

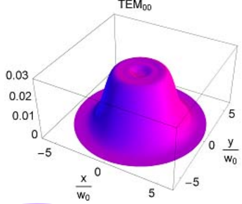




$$S_h \propto \frac{1}{w^n}$$

$$\ell_{clip} = \exp\left[-2\frac{m^2}{w^2}\right]$$

- Detectors limited by fundamental thermal noise
- Spectral density scales as $1/w^n$
  - » n = 1 for the dominant coating losses
- Diffraction prevent dramatically increasing beam size
- Gaussian beams sample only a few percent of the mirror's surface

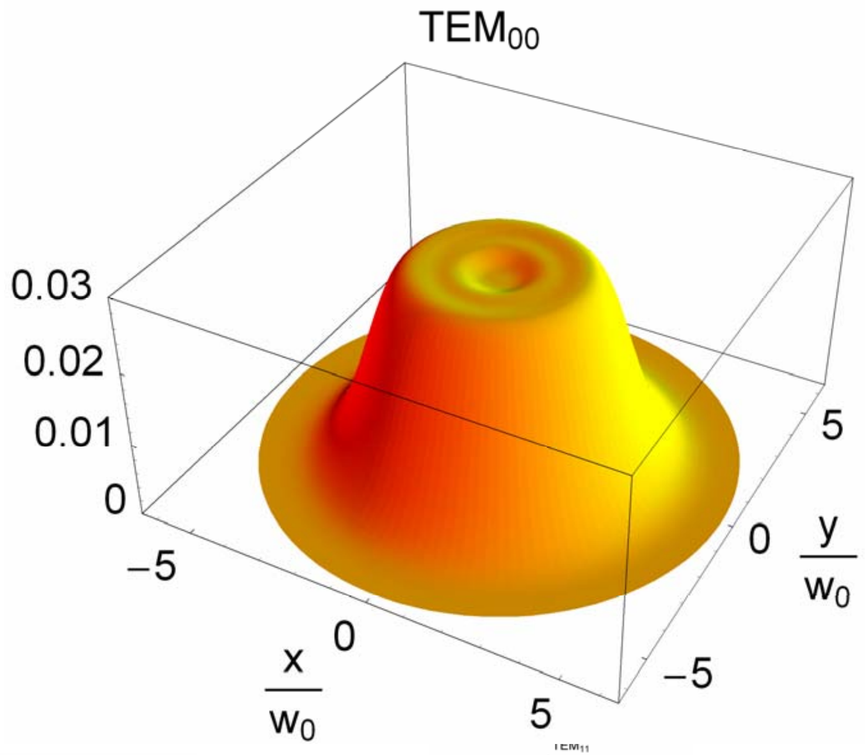


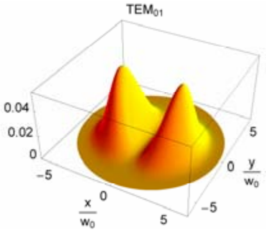
Why mesa beams

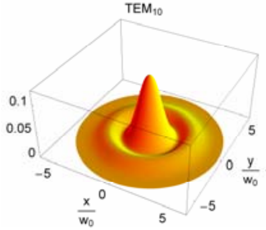
Wider, flatter, and steeper edges beams

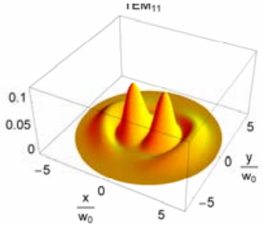
Better average over the mirror surface

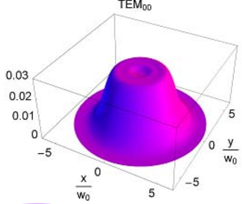
depress thermal noise without compromising diffraction losses





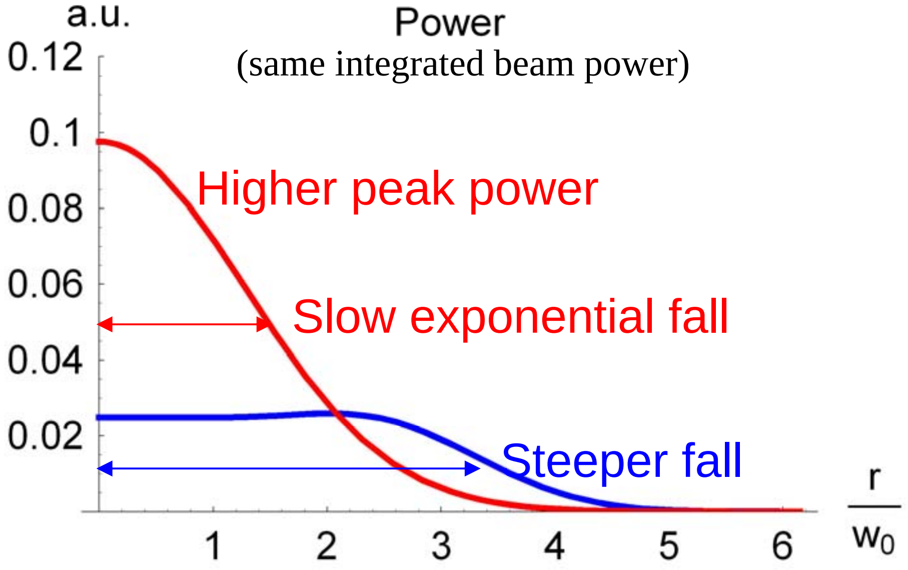


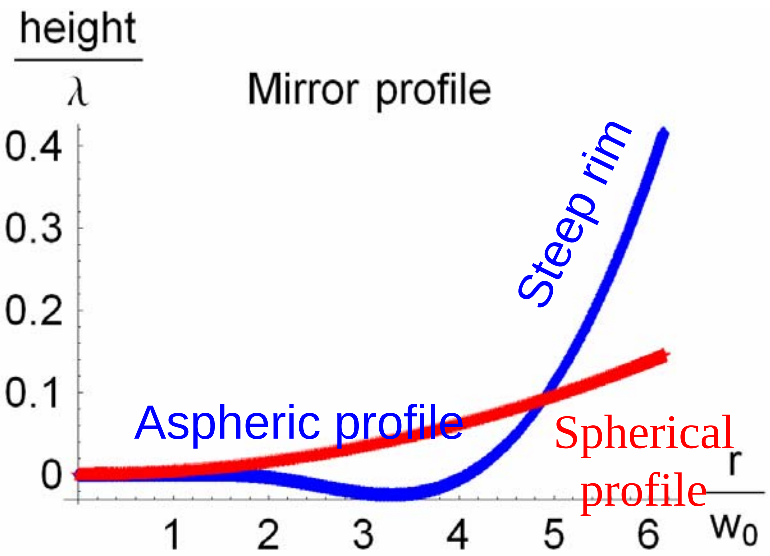




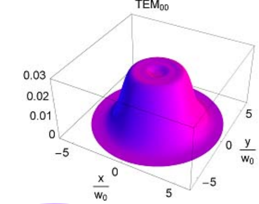
Mesa Beam

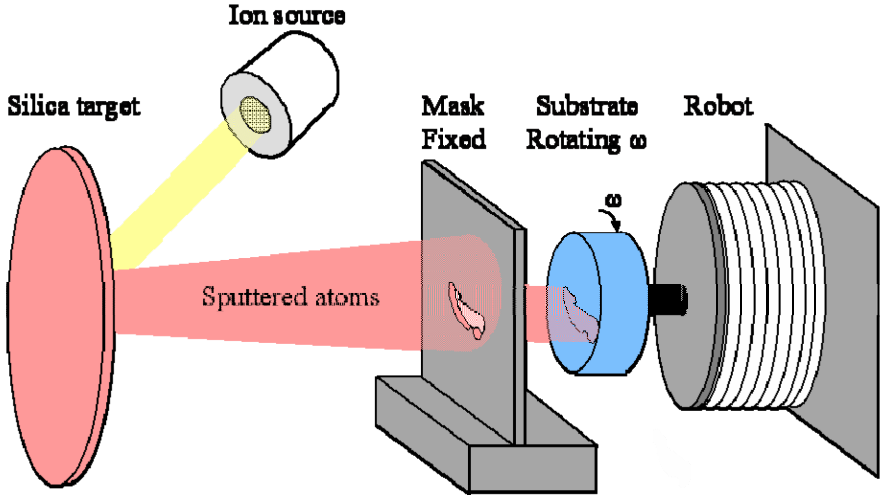
- Optimisation produces the mesa beam



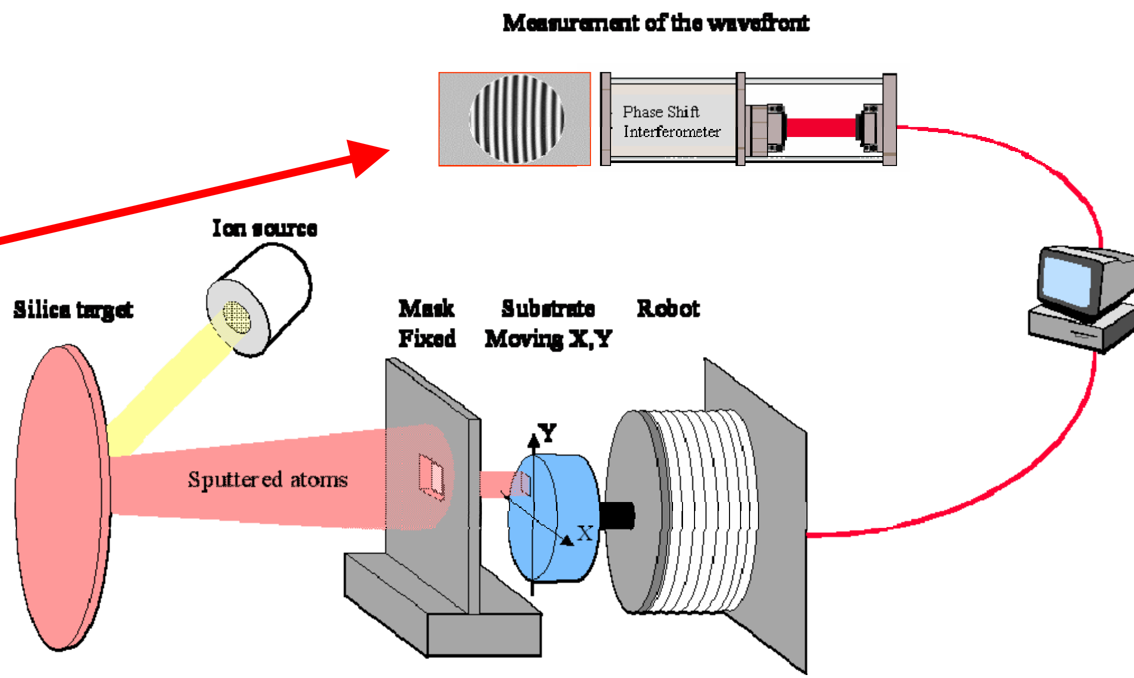


Molecular beam deposited mirror





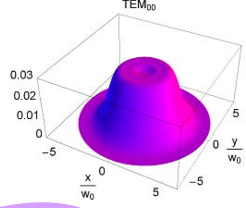
- Profiled Deposition:
  - **Coating the desired Mexican Hat profile using a pre-shaped mask**
  - **precision ~60nm Peak to Valley**



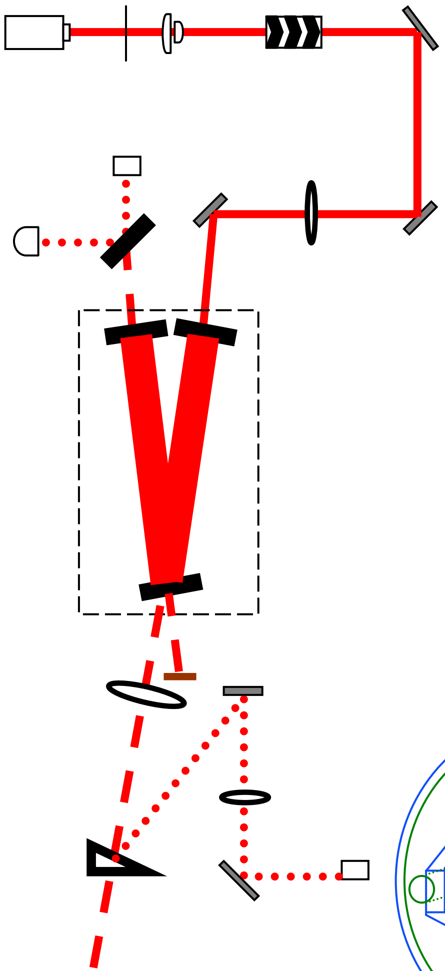
- Corrective coating:

1. **Compare achieved to desired shape**
2. **Correct with molecular pencil**

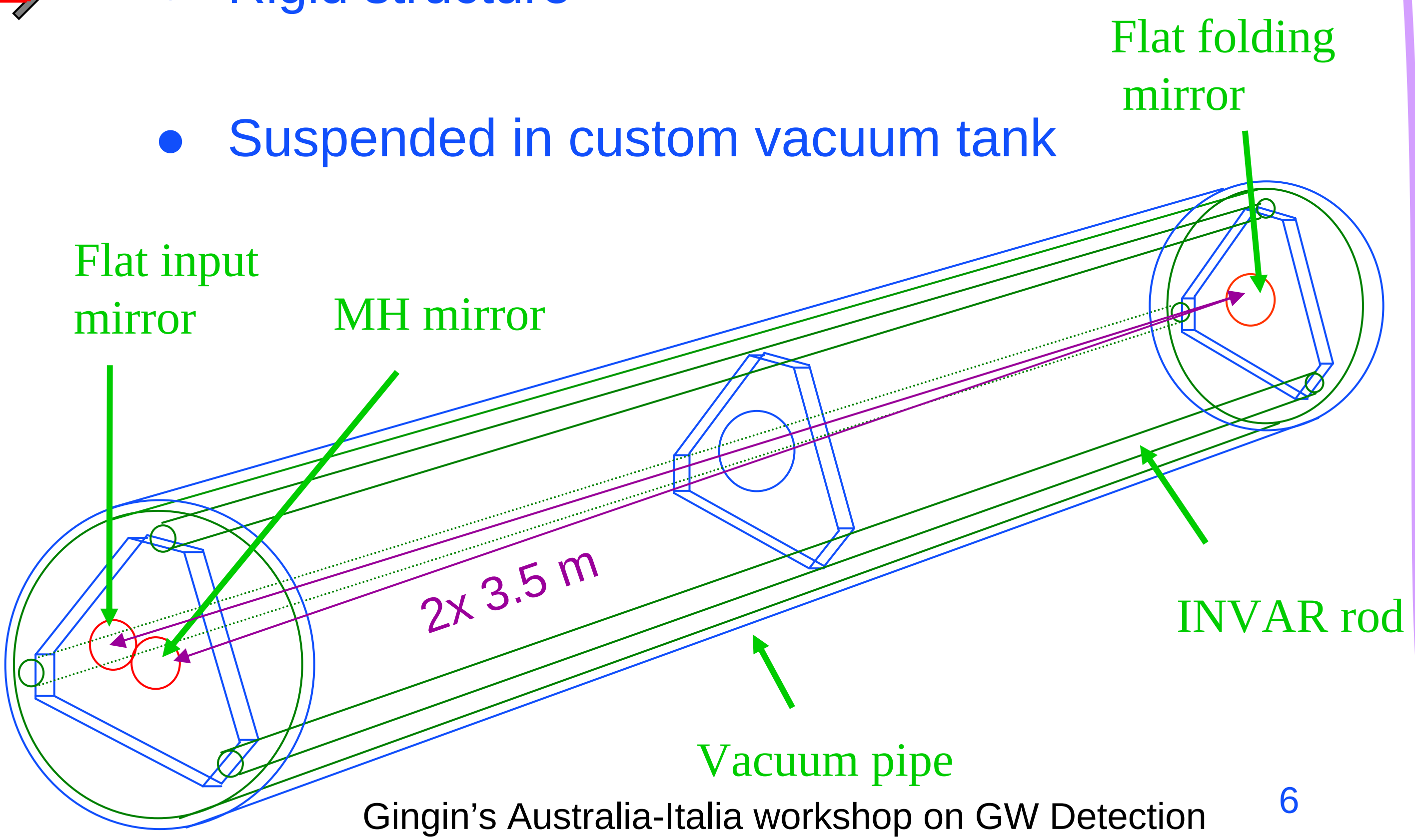
- **precision <10 nm.**



The test Cavity



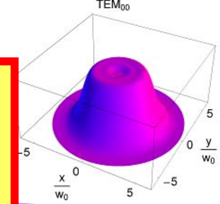
- 7.32 m folded cavity
- Rigid structure
- Suspended in custom vacuum tank

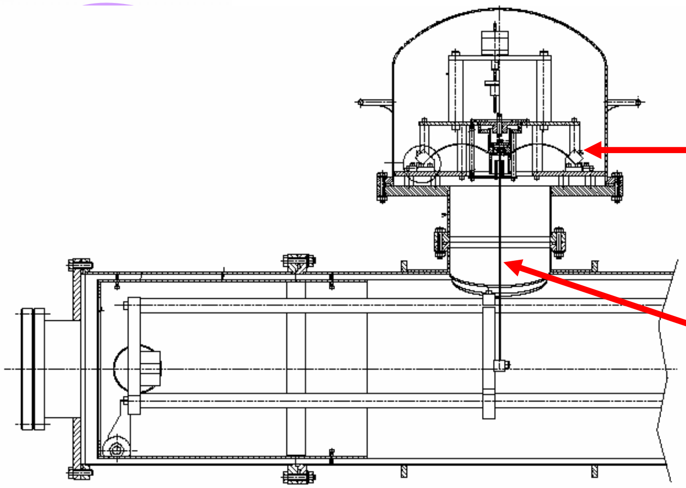


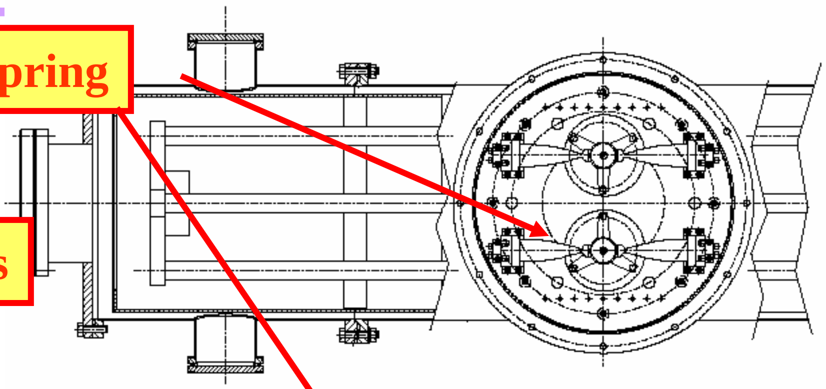
Cavity Suspensions

V~ 0.6 Hz

H ~ 1 Hz

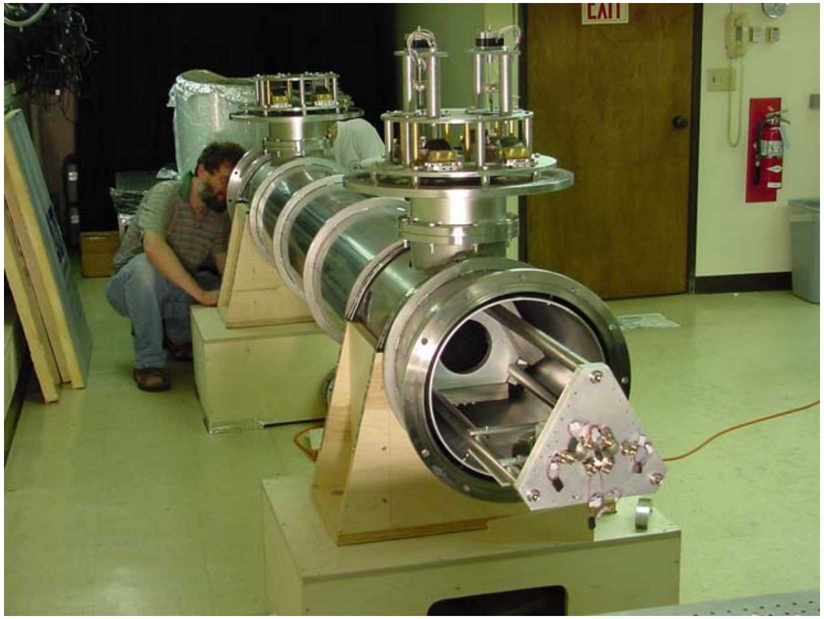


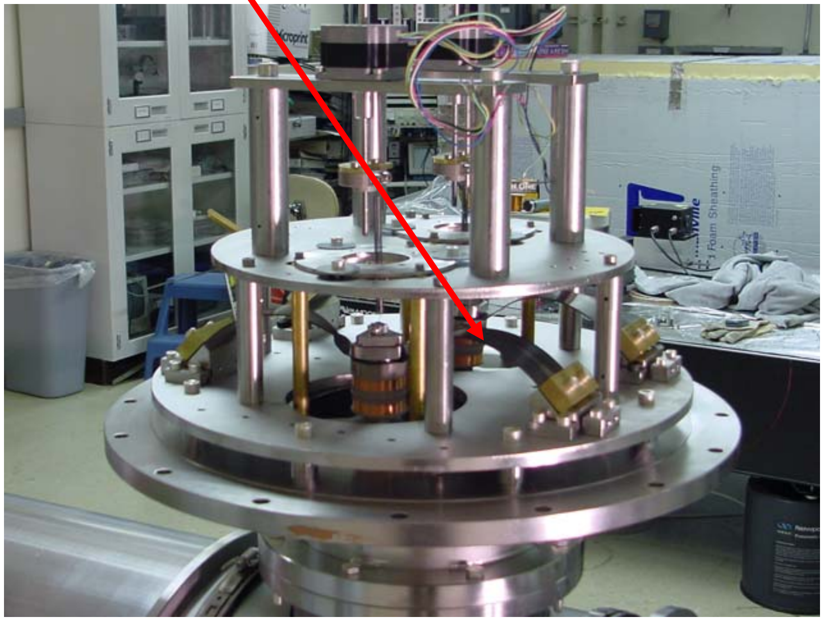




GAS spring

wires





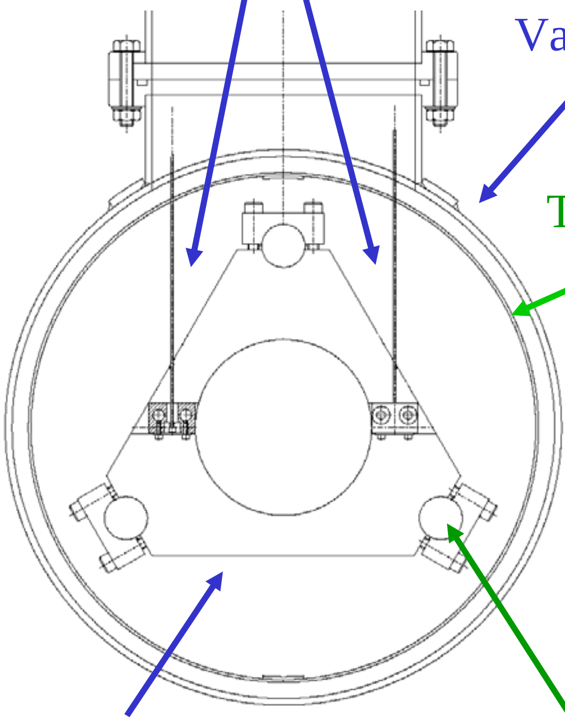
Cavity Vacuum & Thermal Shield

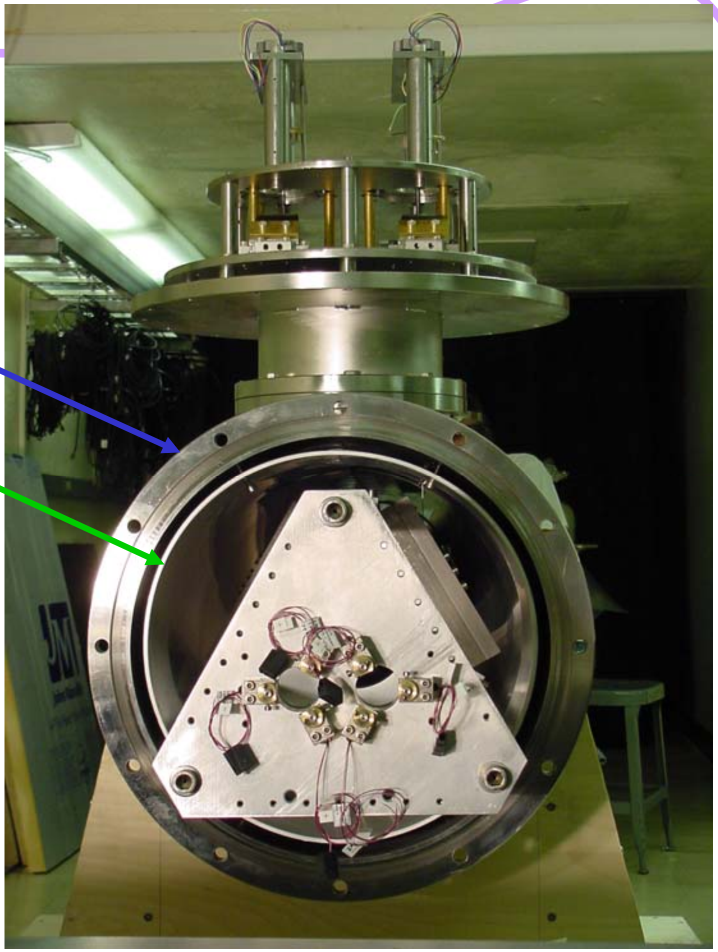
Suspension view

Suspension wires

Vacuum pipe

Thermal shield

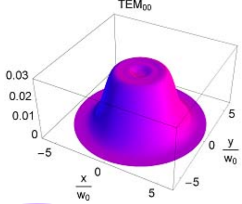


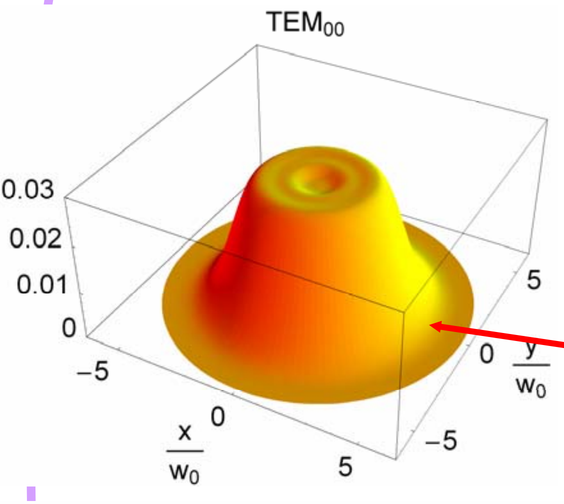


Spacer plate

INVAR rod

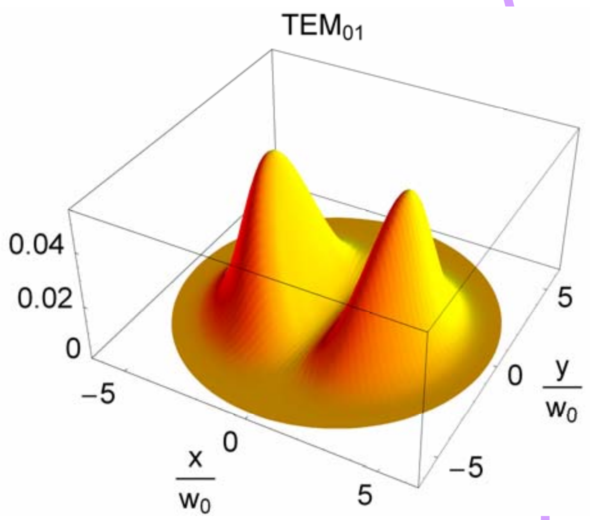
“Mexican hat” mirrors

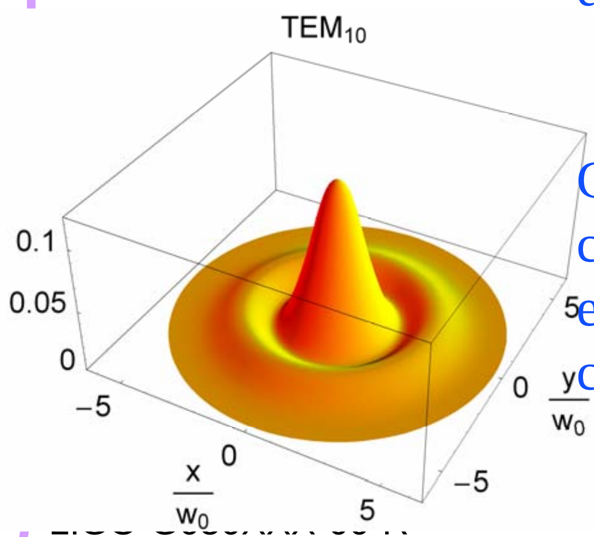




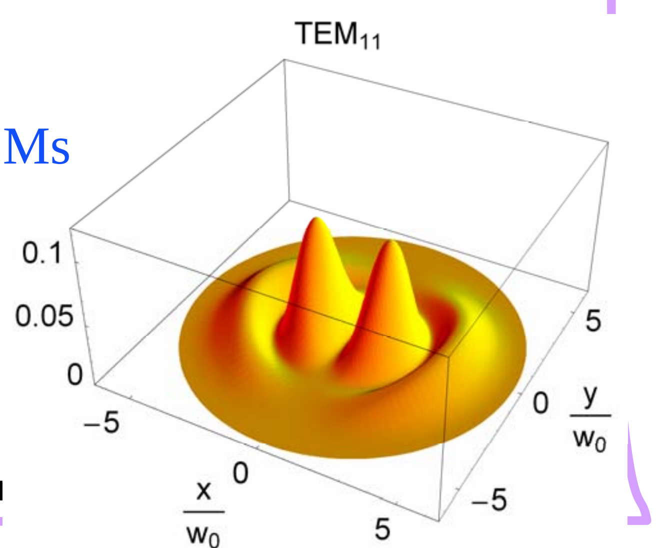
Numerical eigenmodes for a ideal MH Fabry-Perot interferometer:

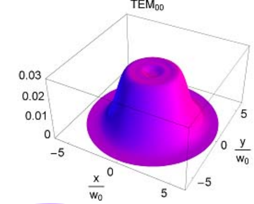
The fundamental mode is the so-called “Mesa Beam”, wider and flatter than a gaussian power distribution





Cylindrical symmetry yields TEMs close to the Laguerre-Gauss eigenmodes set for spherical cavities



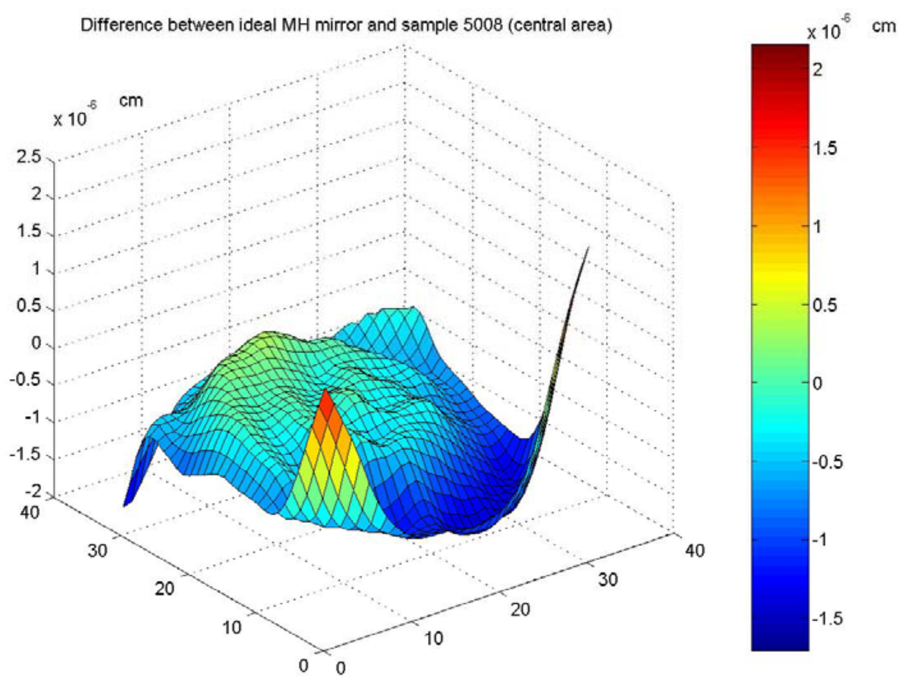


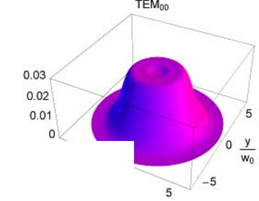
“Mexican hat” mirrors

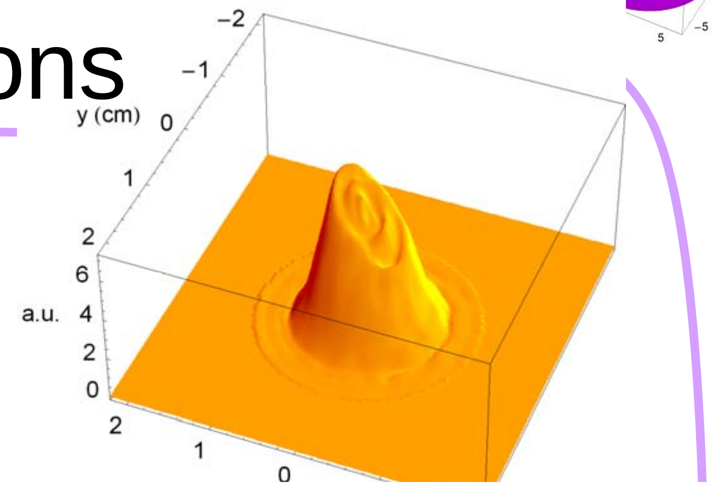
- LMA laboratories provided three mirror prototypes
- All affected with several imperfection
  - » Due to the excessively small mirror size
- Beam Tested one with a not negligible slope on the central bump
- First simulated using paraxial approximation to evaluate how mirrors with these imperfections would affect the resonant beam

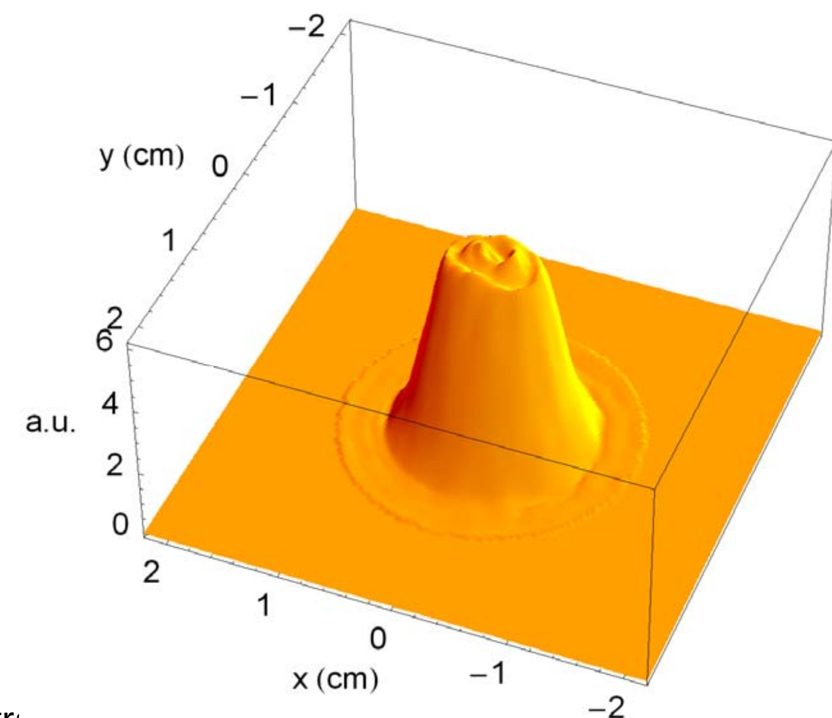
FFT simulations

- The slope on the central bump can be corrected applying the right mirror tilt

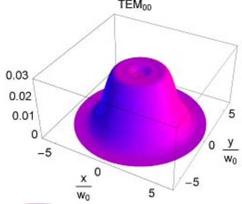




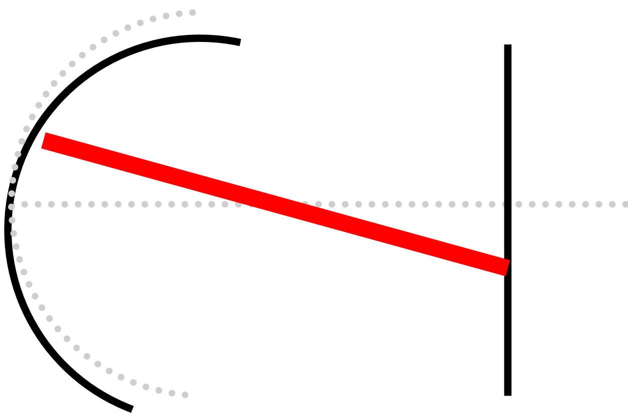


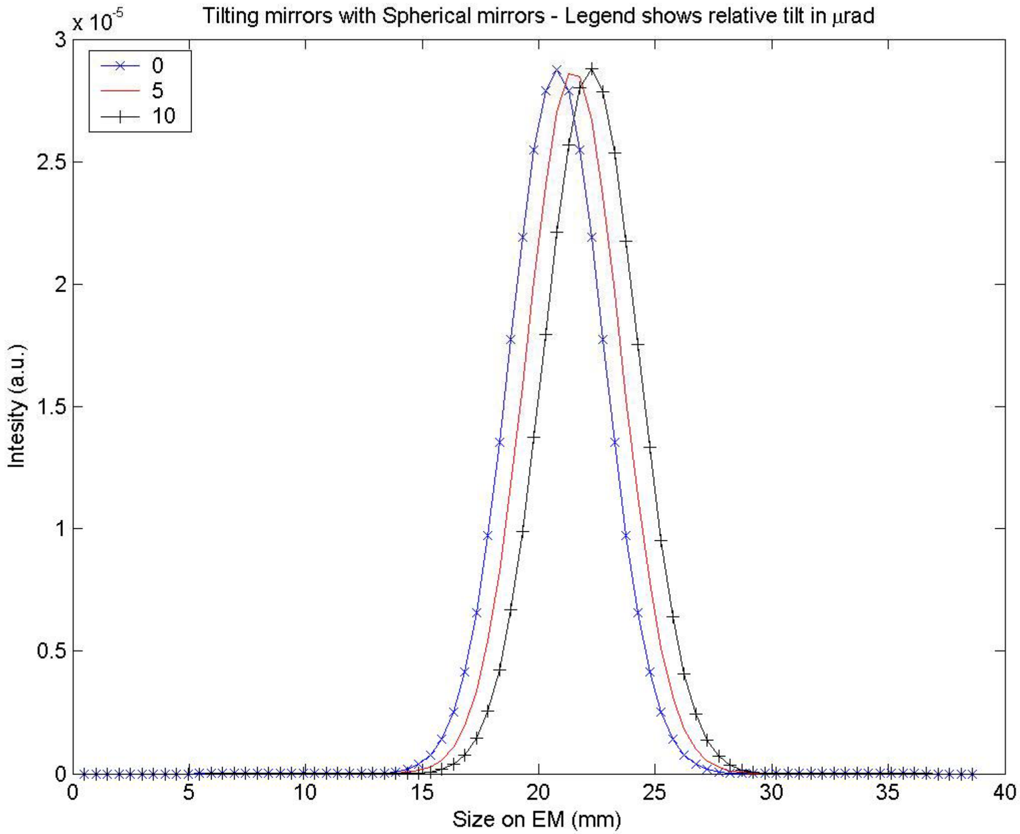


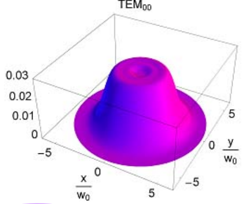
Tilts of Spherical Mirrors



- Tilts of spherical mirrors only translate optical axis



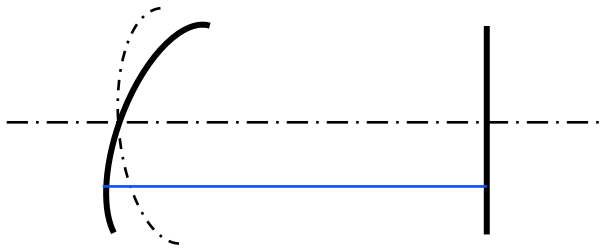




MH Cavity Alignment

- Tilt on MH mirrors destroys cylindrical symmetry

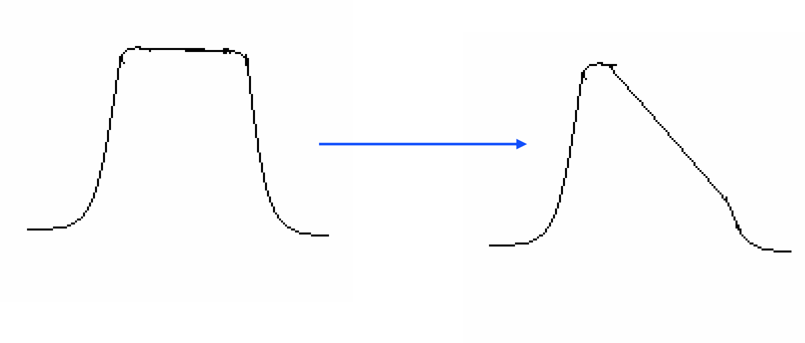
-> resonant beam phase front changes with the alignment

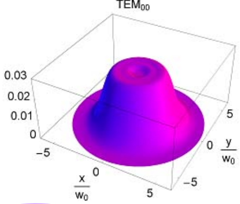


- Folded cavity: no obvious preferential plane for mirrors alignment

-> very difficult align within required ❍rad precision

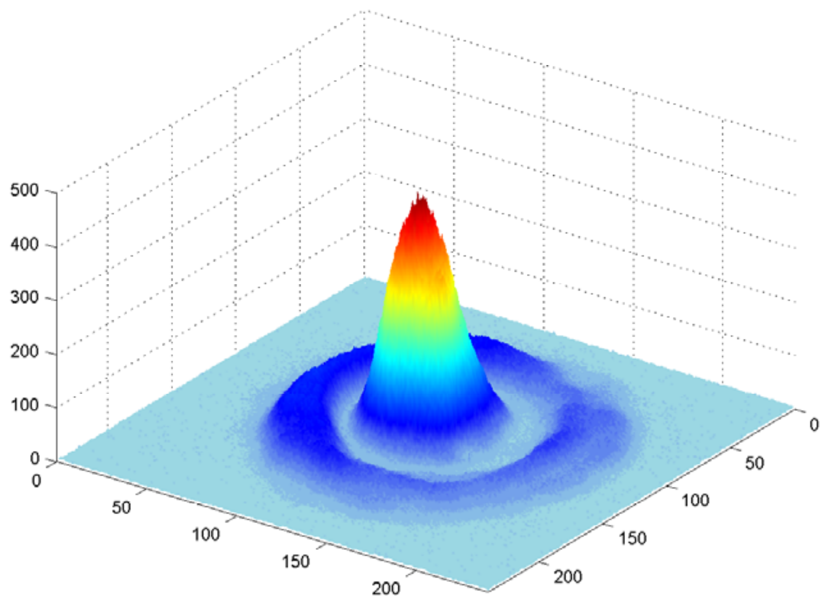
=> TEM_{00} difficult to identify

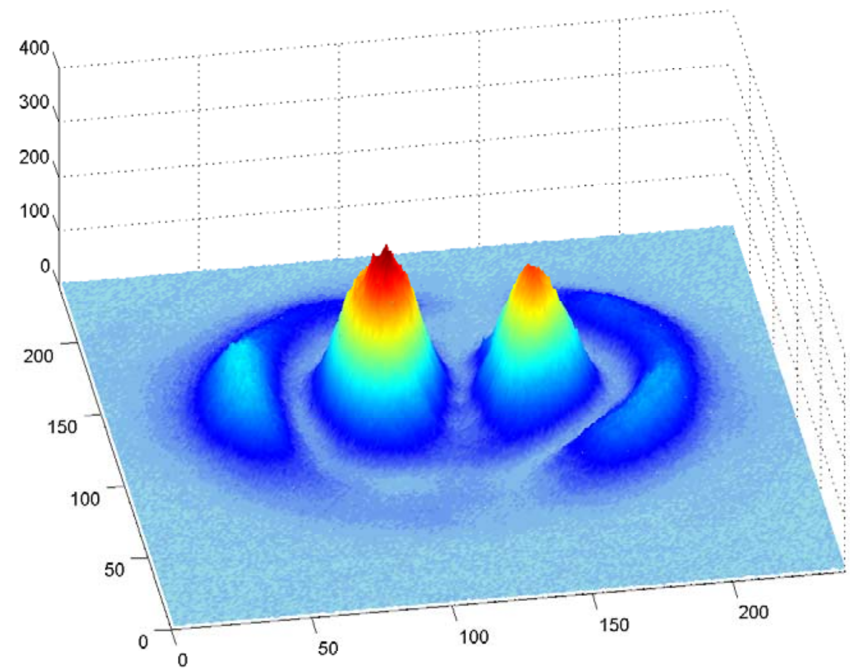


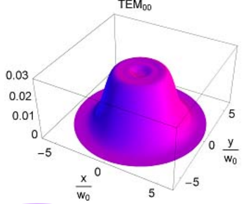


Experimental Results

- No stable Mesa beam profile was initially acquired
- Higher order modes were found very easily



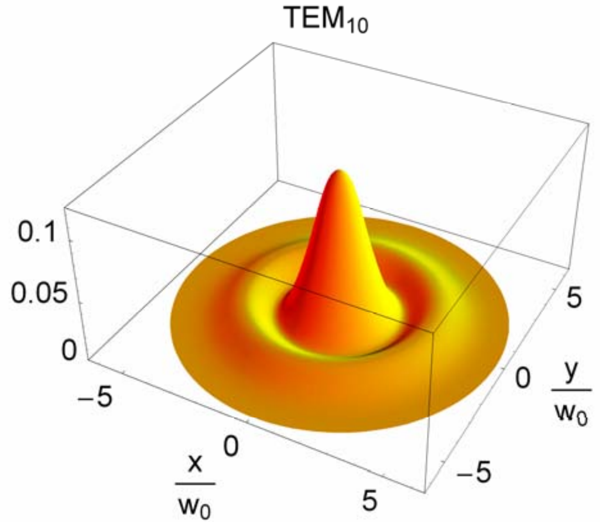


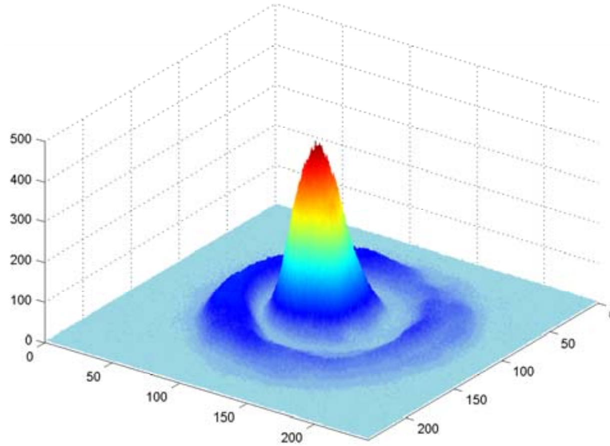


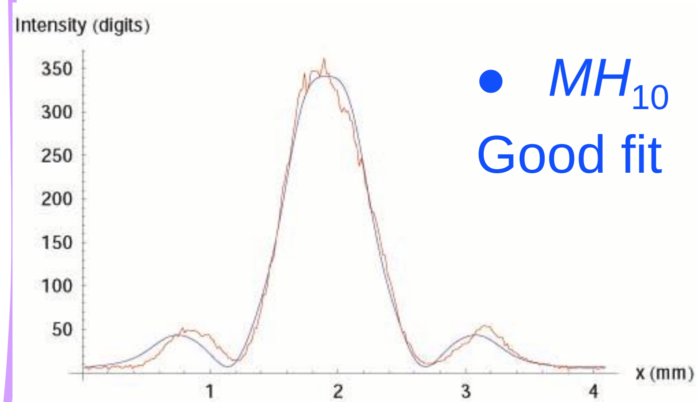
Results

- These modes exhibit good agreement with theory

TEM_{10}

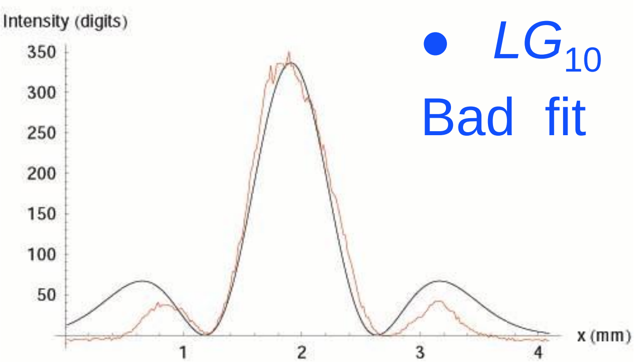






- MH_{10}

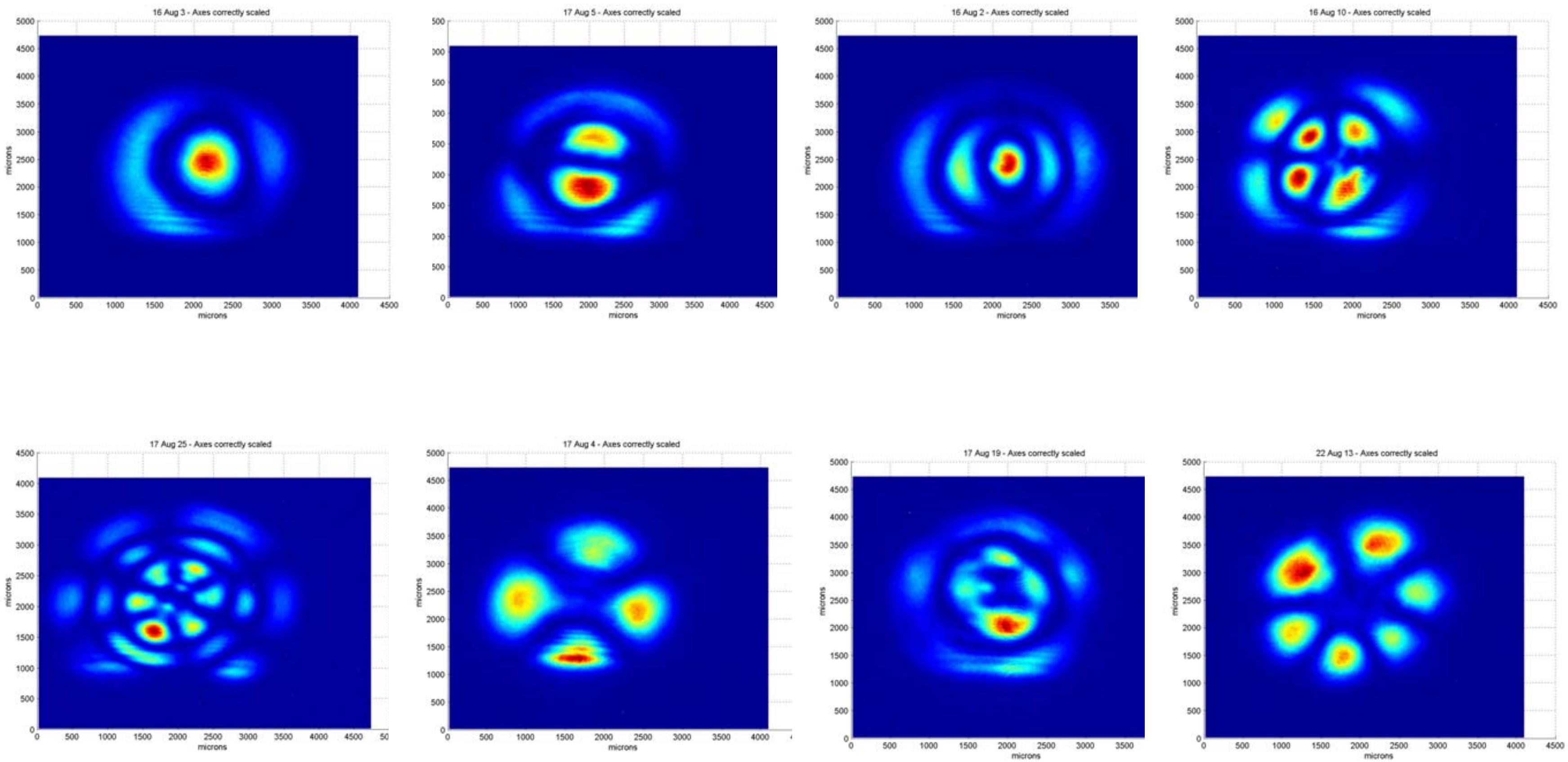
Good fit



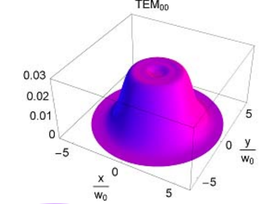
- LG_{10}

Bad fit

Results - other HOM

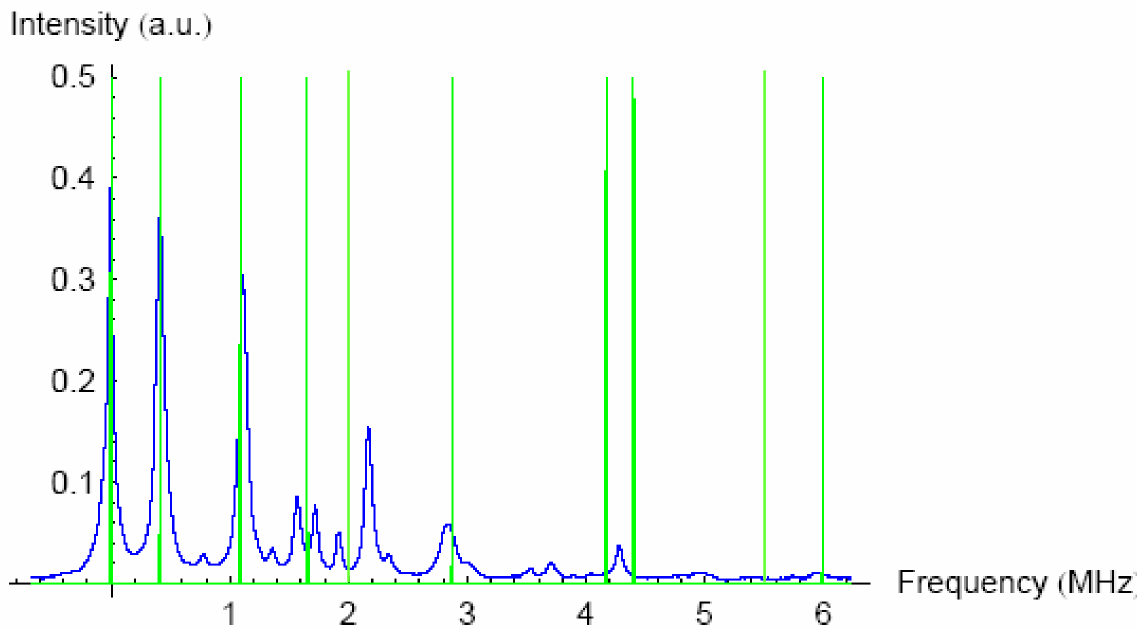


Diffraction around beam baffle eliminated

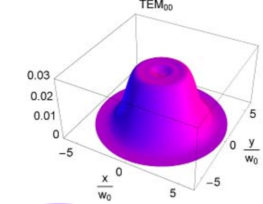


Chasing the TEM_{00}

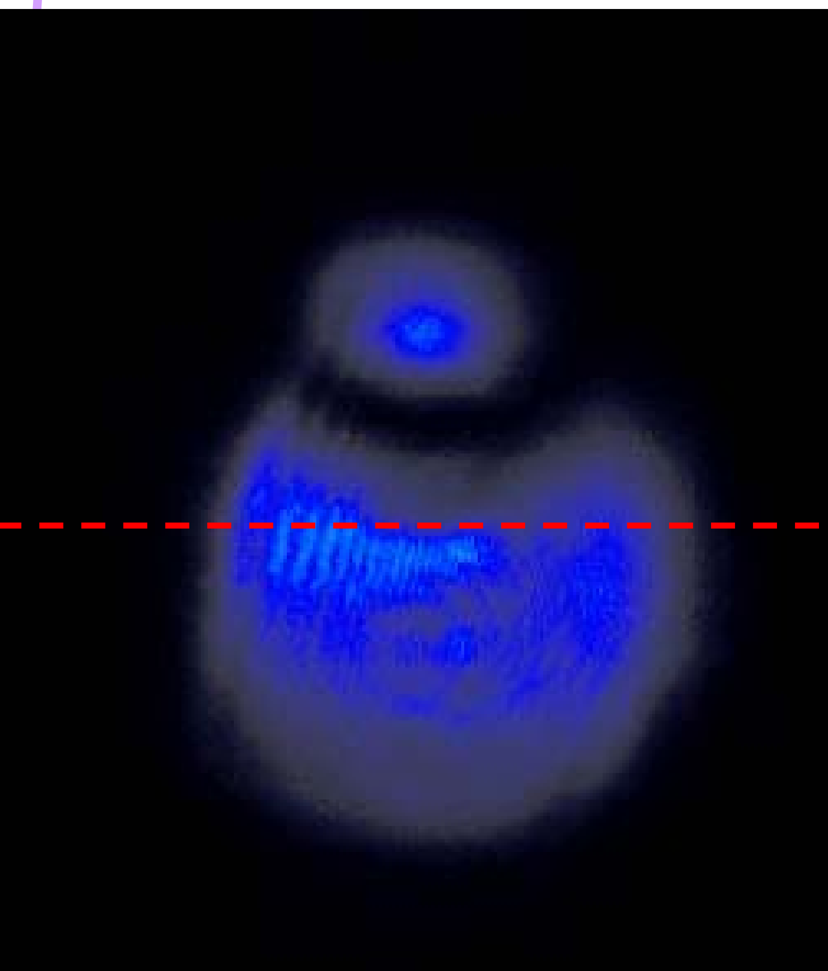
- Apply FP spectrum analysis:
- TEMs identification and coupling analysis
- Non-symmetric spacing: as expected
- TEM_{00} is the first of the sequence, independently of its profile appearance

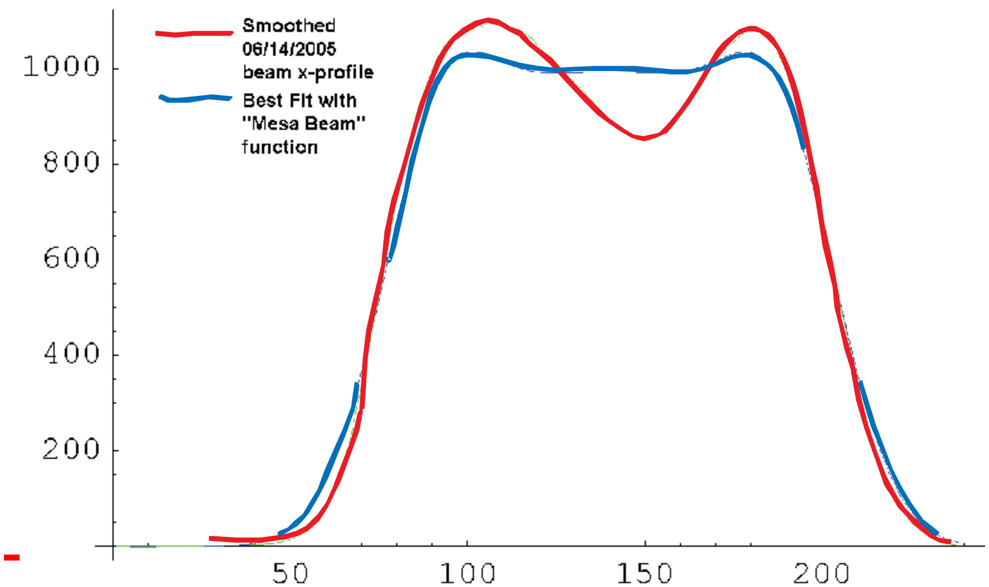


$$\Delta\nu_{FSR} = 20.5 \text{ MHz}$$



Chasing the TEM$_{00}$

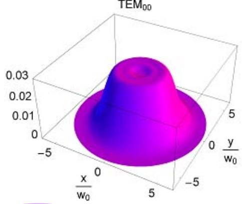


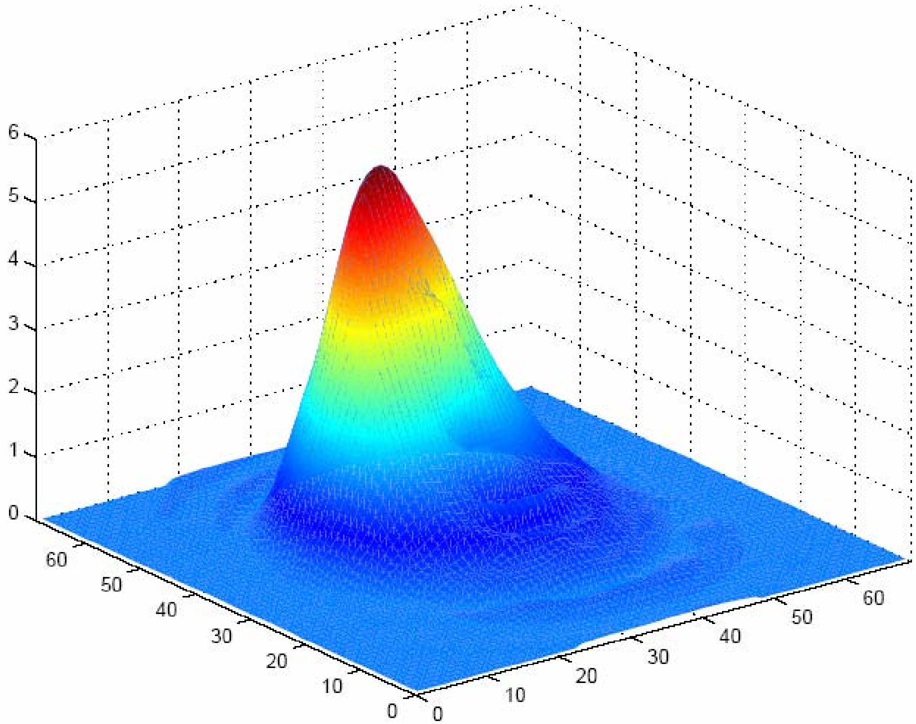


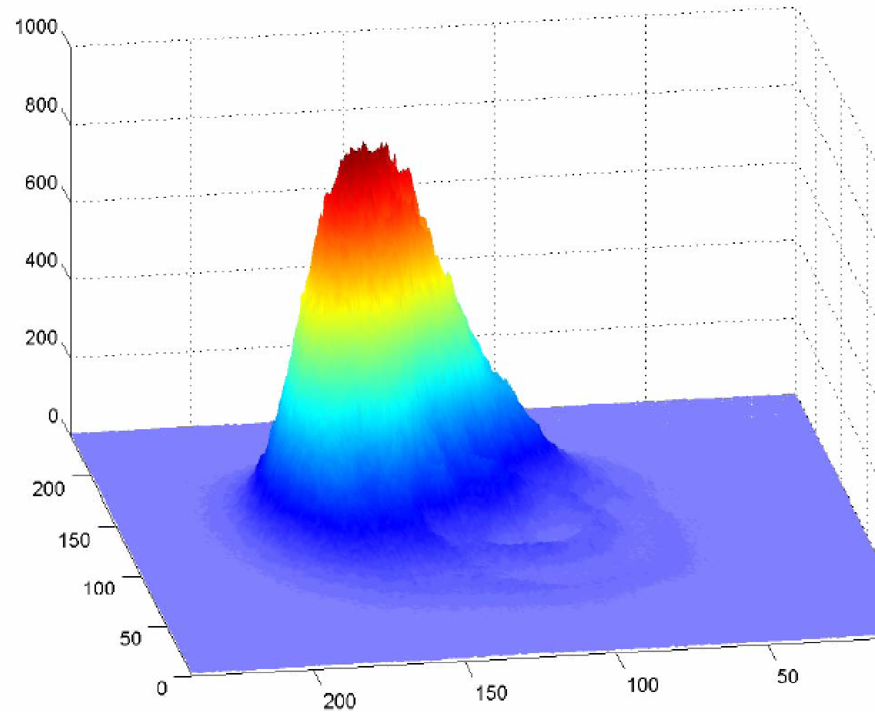
2-dimensional nonlinear regression:

Definitively not Gaussian

Experimental Results

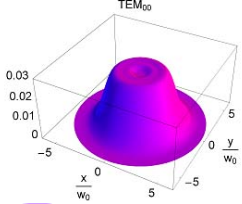




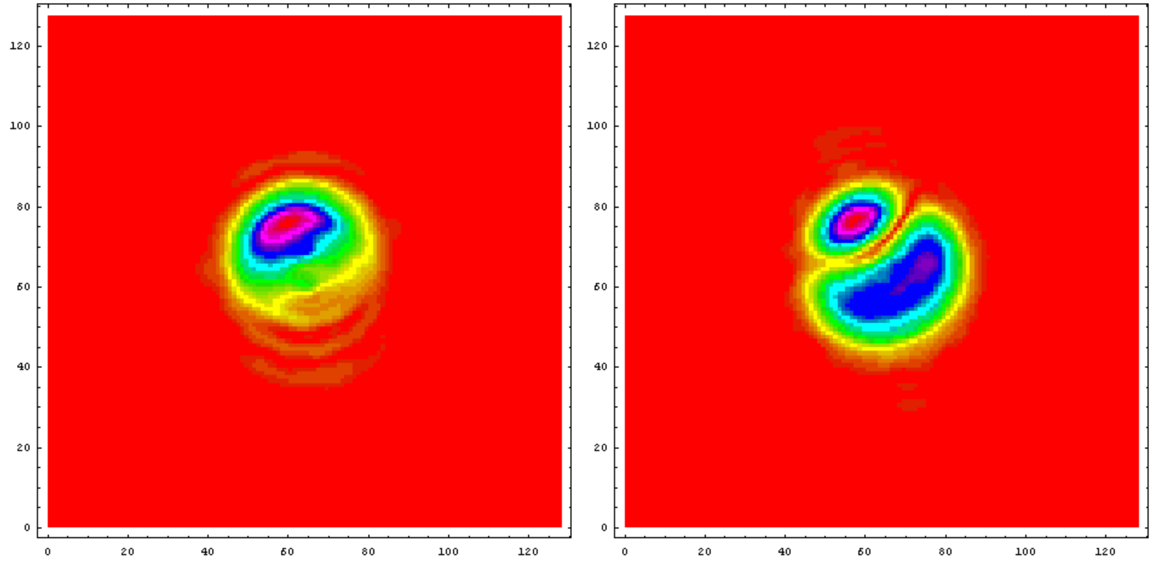


- TEM00 tilt simulation 4μrad tilt   TEM$_{00}$ data

Systematic and next steps



- Any attempt to “drive” the beam in a centered configuration failed
- cylindrical symmetry is definitely not achievable
- FP spectrum analysis: peaks are separated enough -> we are observing the actual TEM_{00}cavity modes

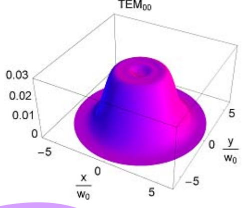


input offset + 0.2 cm

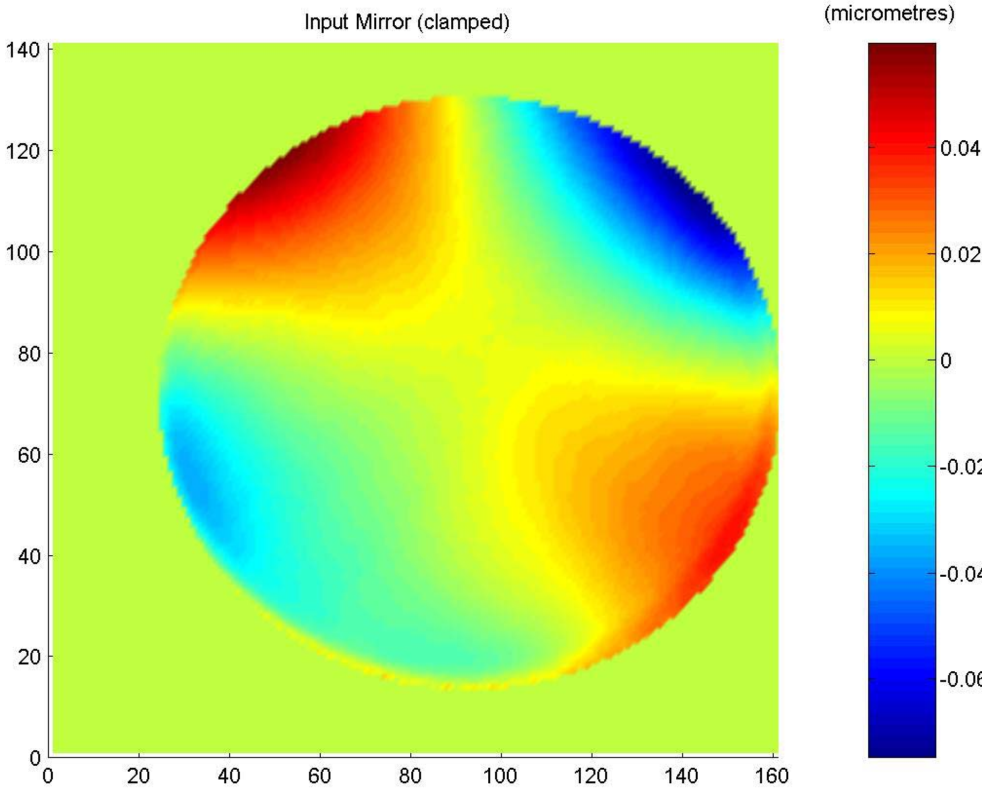
input offset -0.2 cm

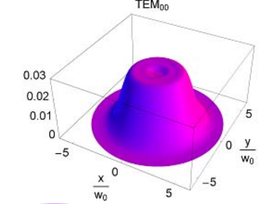
finesse = 623 input beam =

Cause of cylindrical symmetry loss

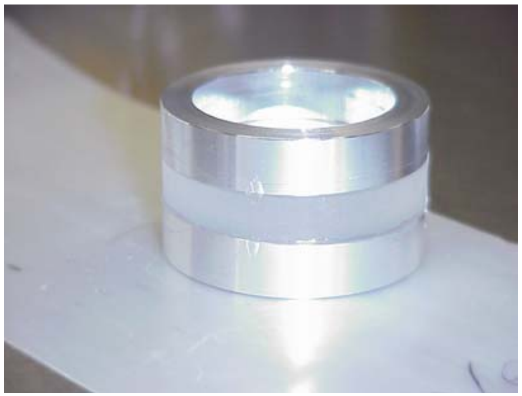


- Mechanical clamping stress deform the folder and input mirrors
- ~ 60 nm deformation -> three times the height of the MH central bump
- Marked astigmatism is induced
- FFT simulation with actual IM profile confirm problem

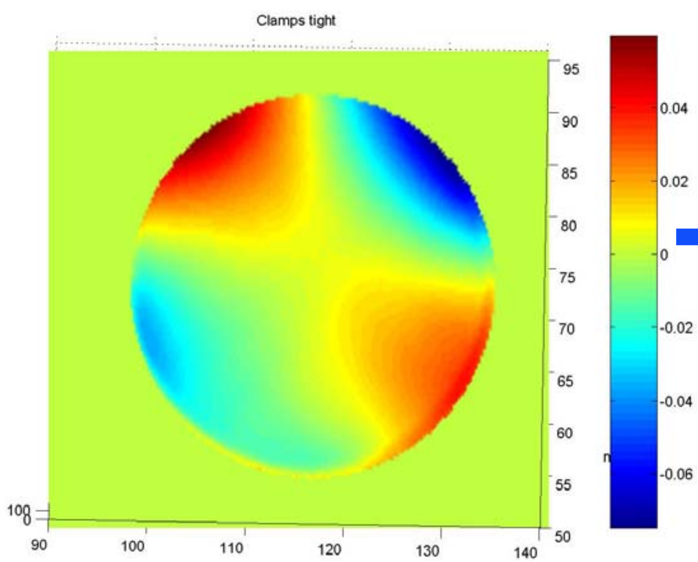


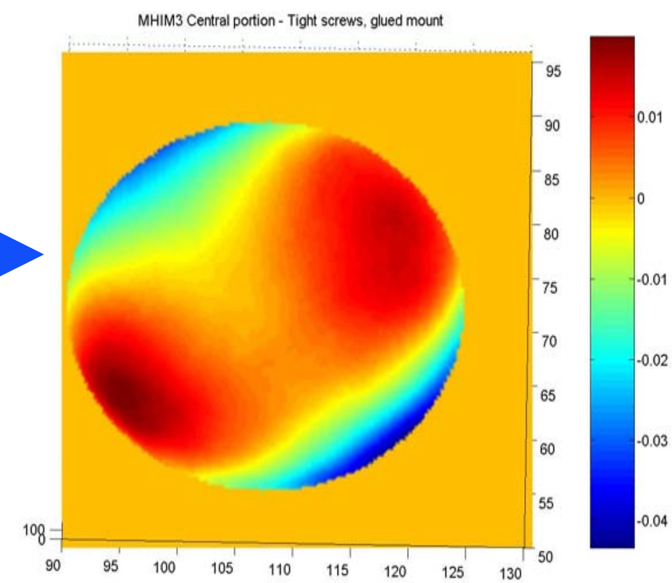


Solving the problem



- Flat mirrors too thin (1 cm)
- Temporary fix: Distributed stress with aluminum rings
- Thicker substrates ordered

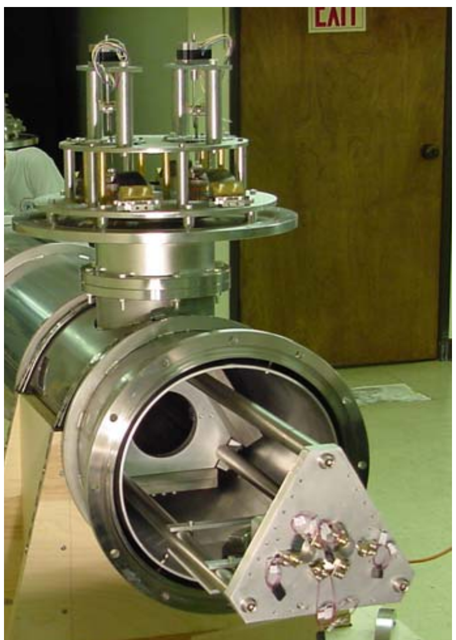


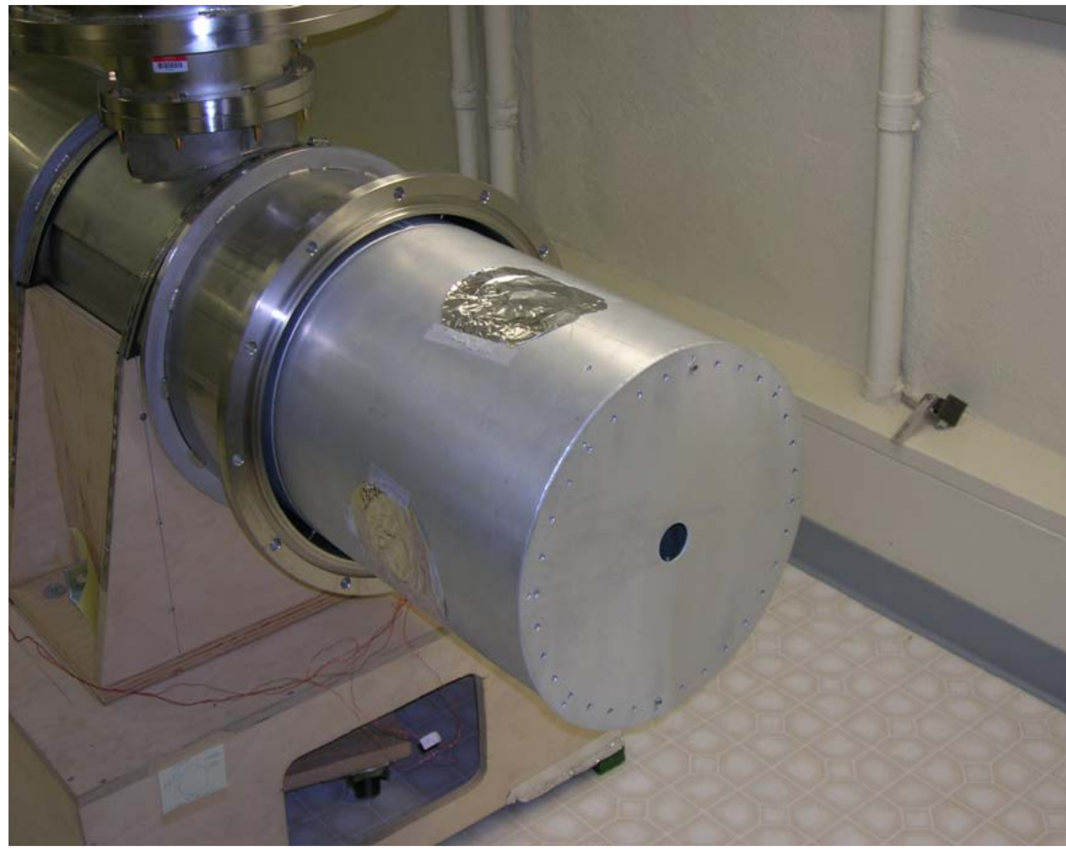


LIGO

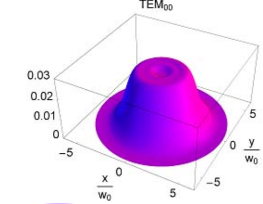
Other improvements

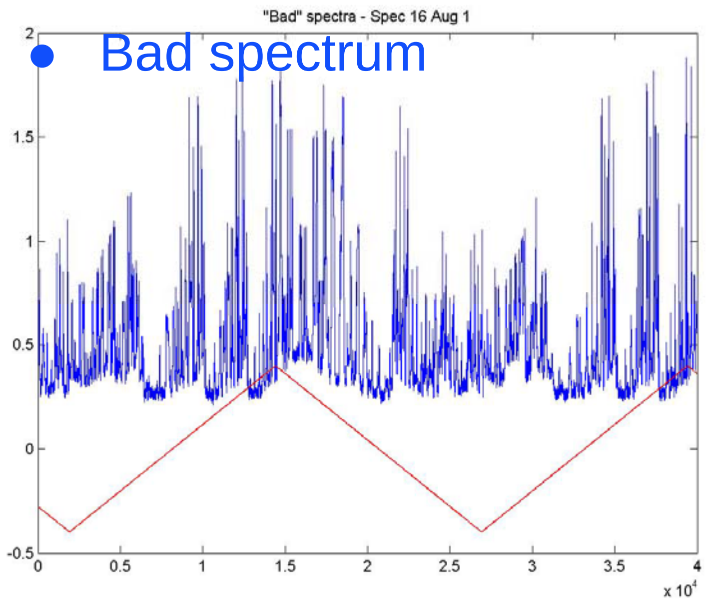
- Improved atmospheric isolation
- Better stability ‘in lock’



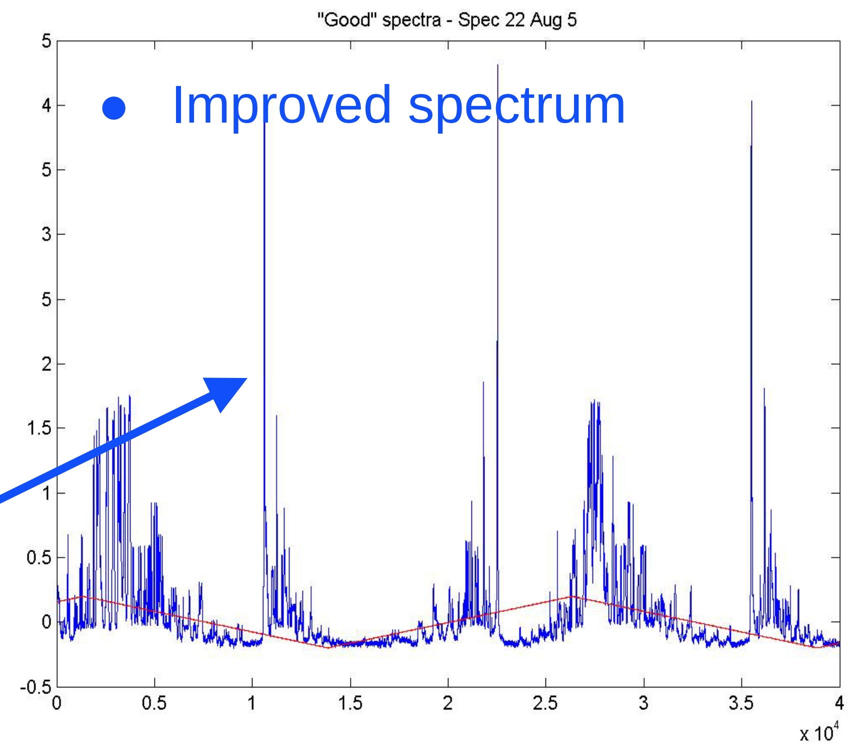


Passing from Side to Dither lock



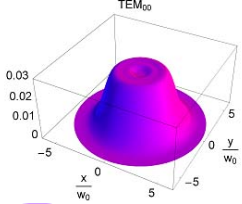


- Bad spectrum



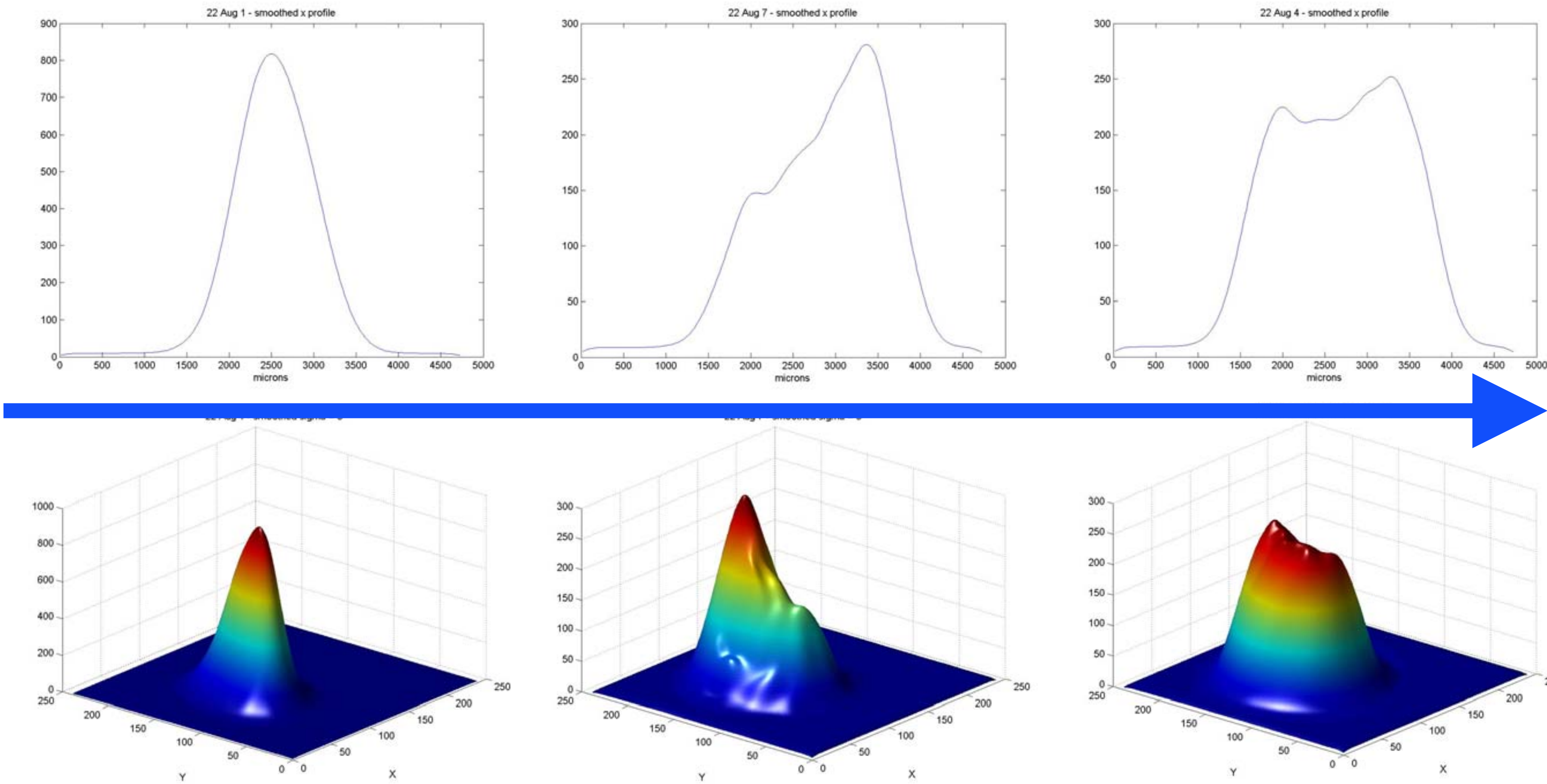
- Improved spectrum

- More power in the fundamental mode
- Now can lock on the TEM_{00} mode

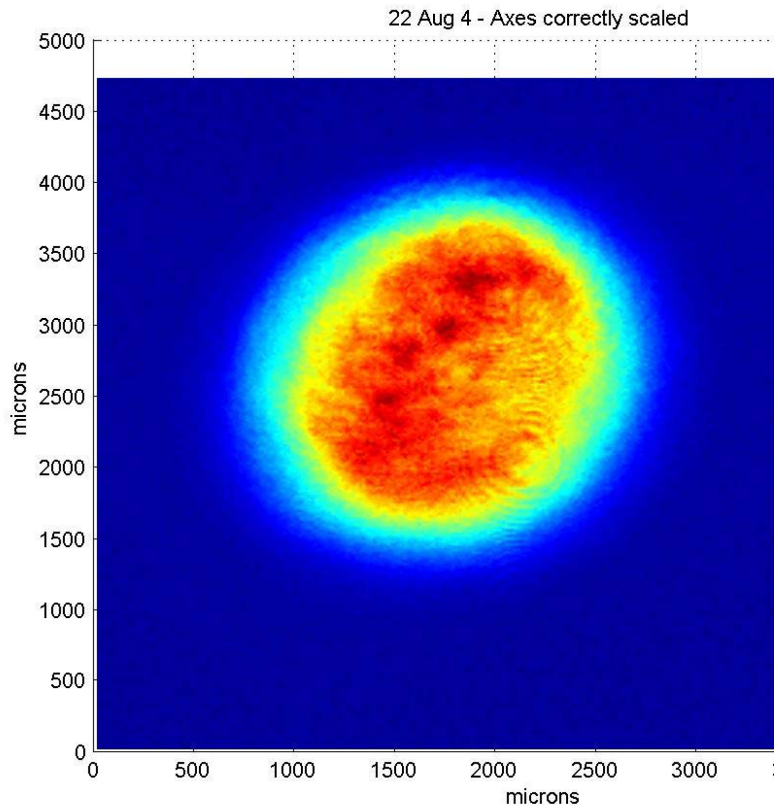


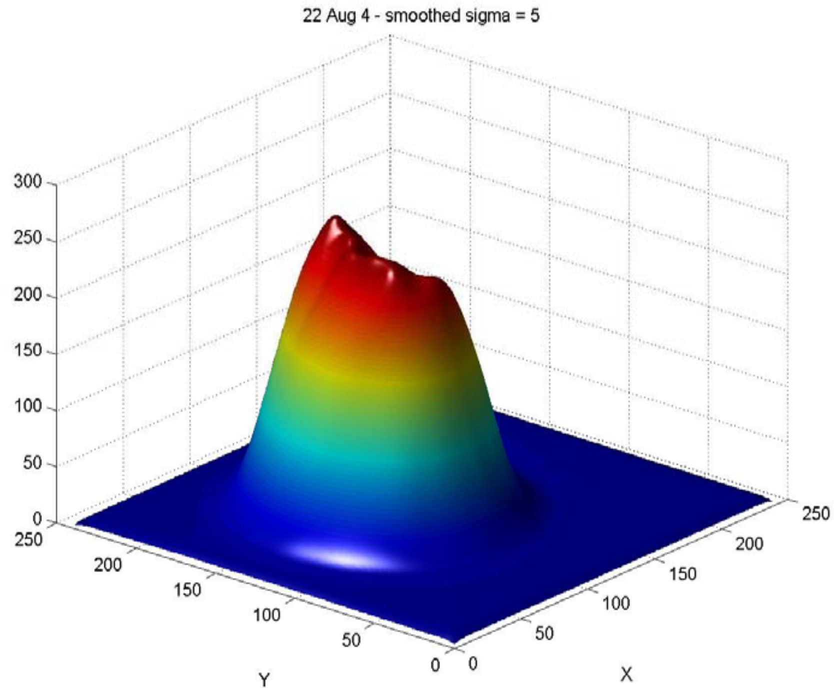
Improving Alignment

- The reference during alignment was changed from the intensity profile to the transverse mode spectrum

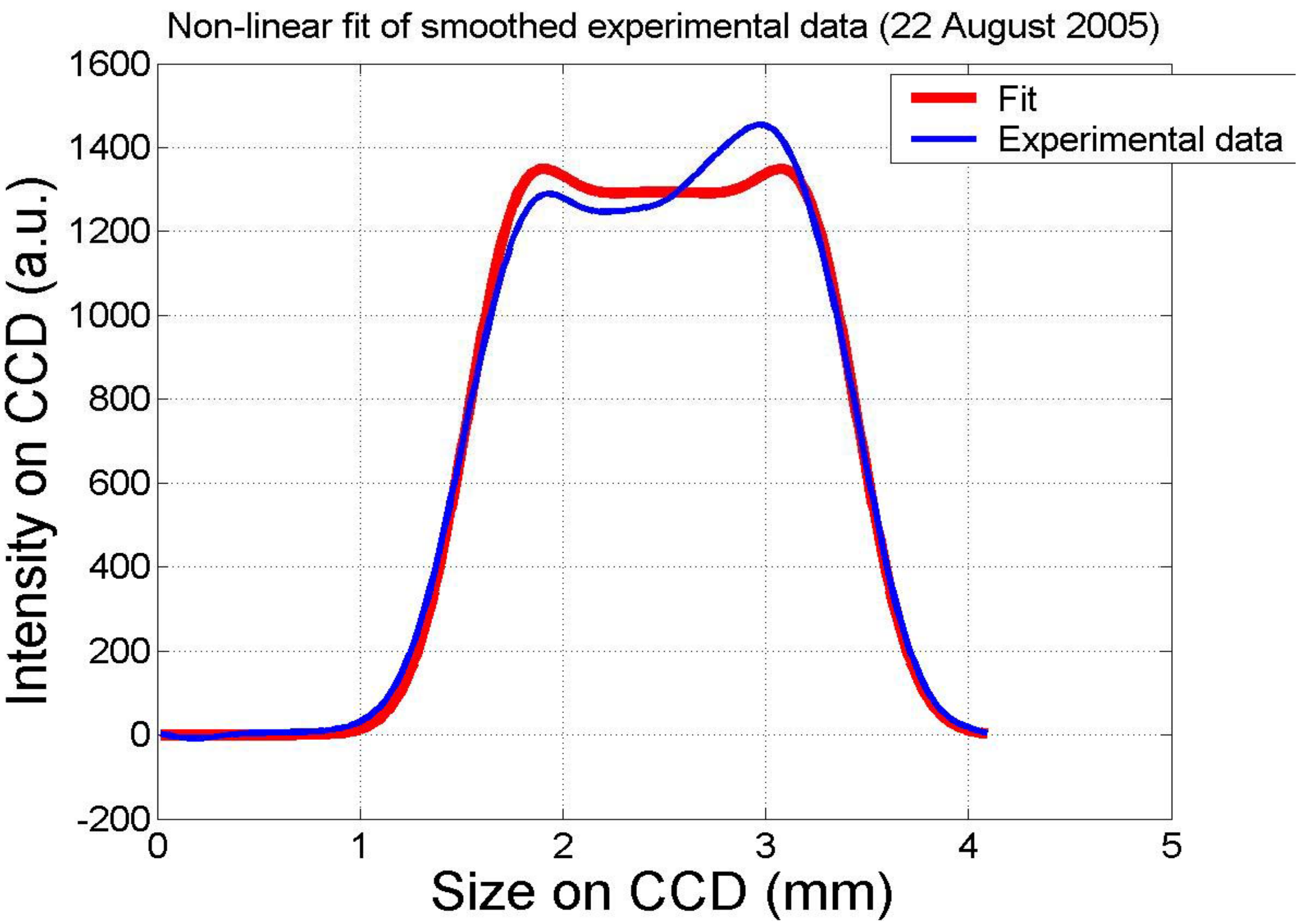


The First Mesa Beam

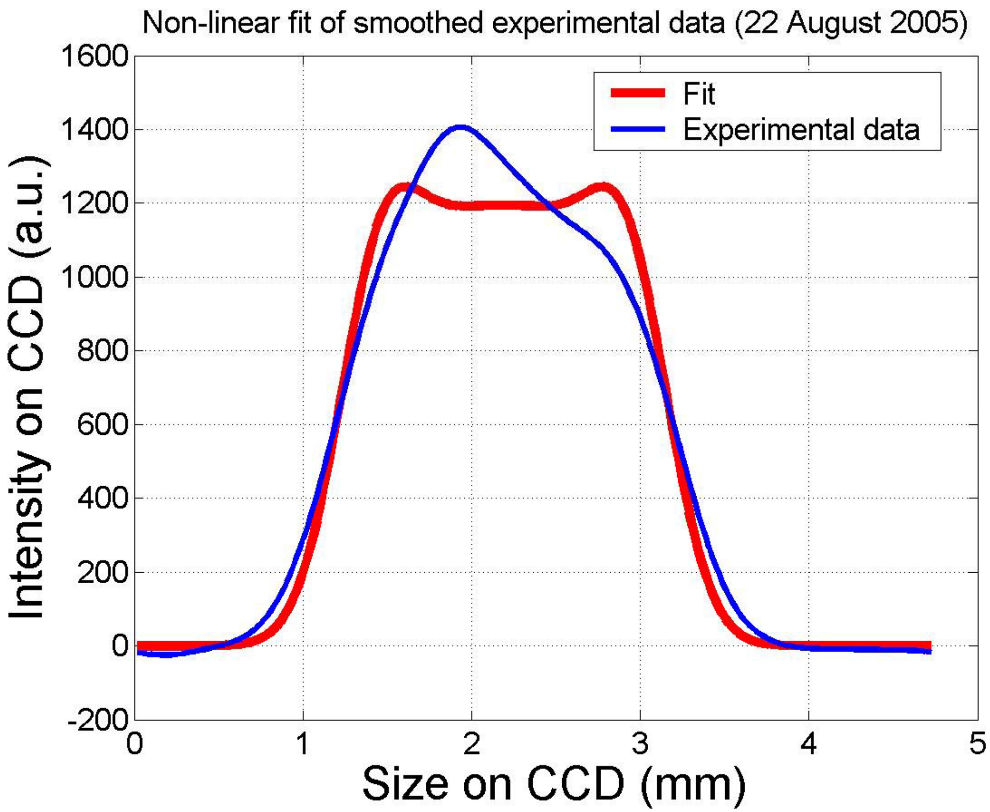


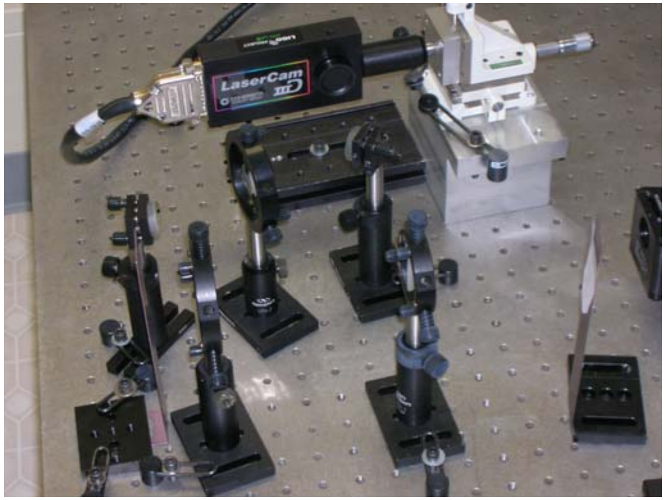


Non-Linear Fit X



Non-Linear Fit Y

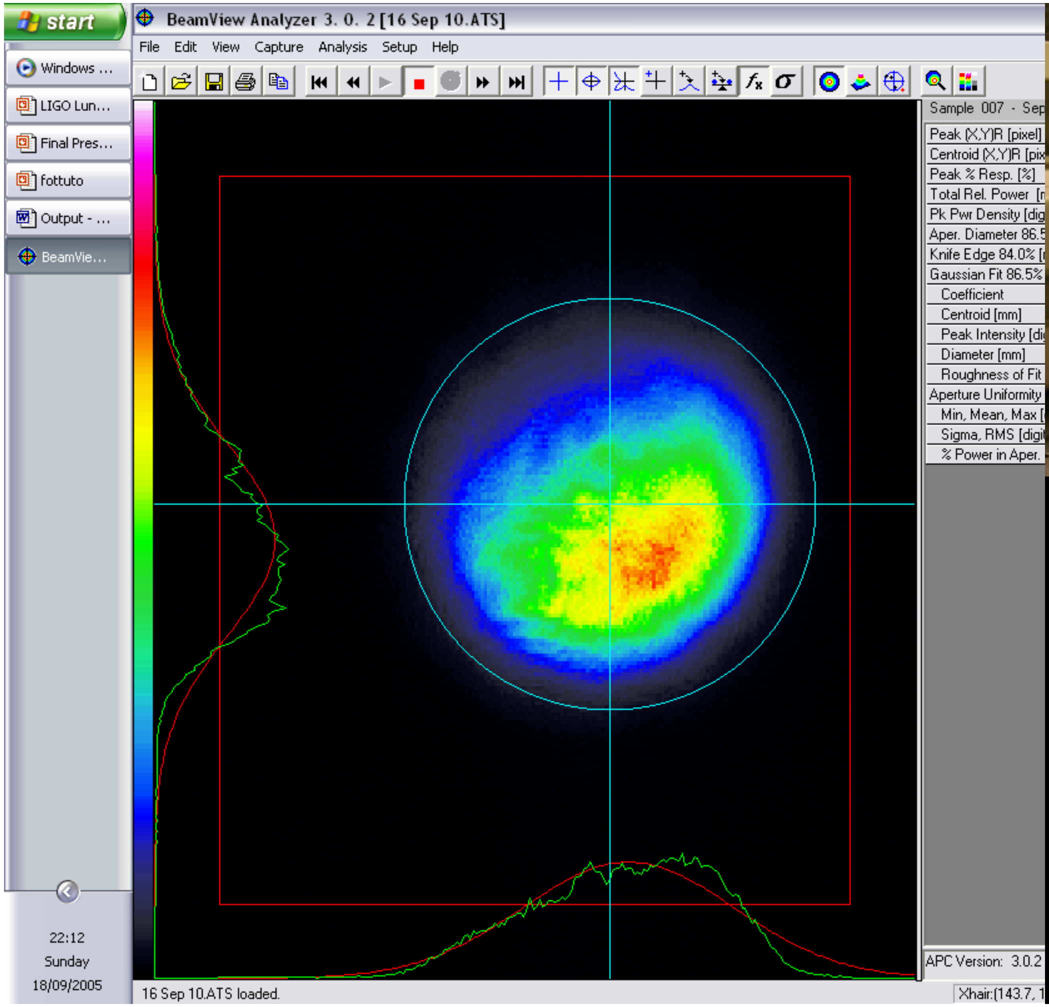




$$w_{theory} = 6.68mm$$

$$w_{experiment} = 7.60 \pm 1.19mm$$

Alignment



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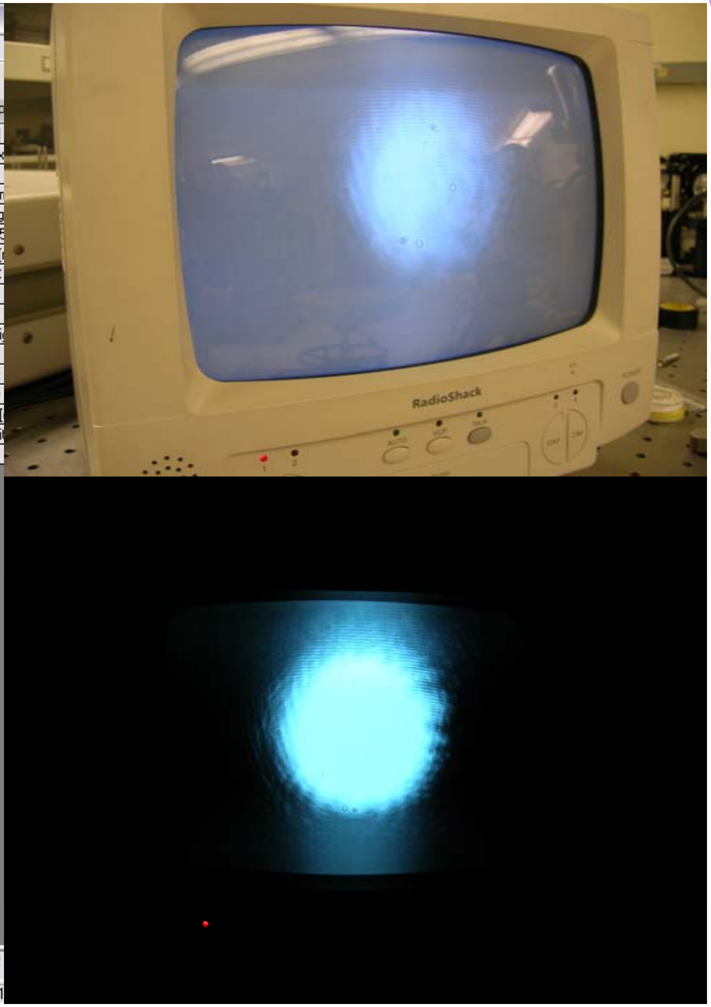
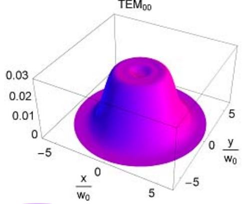
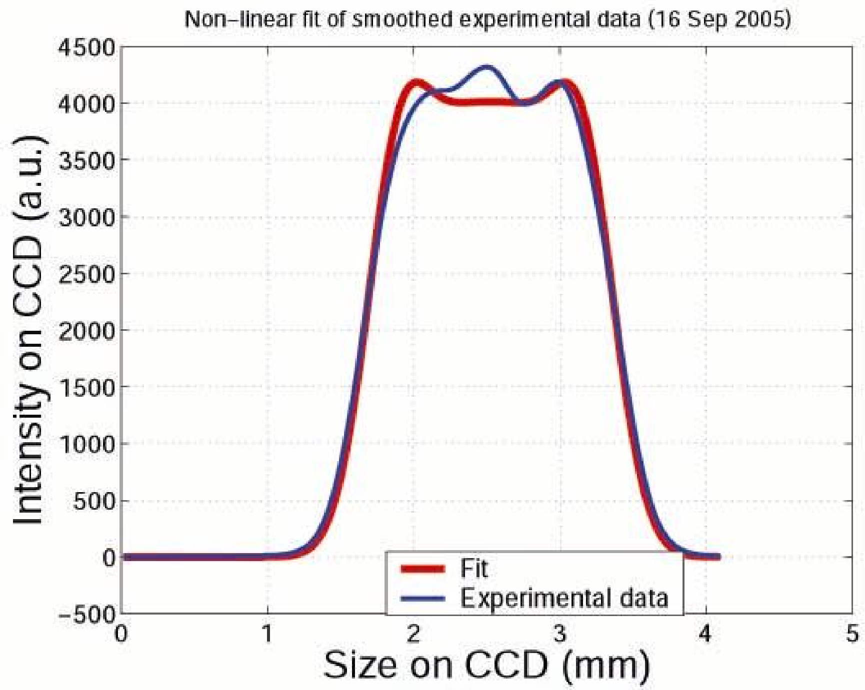
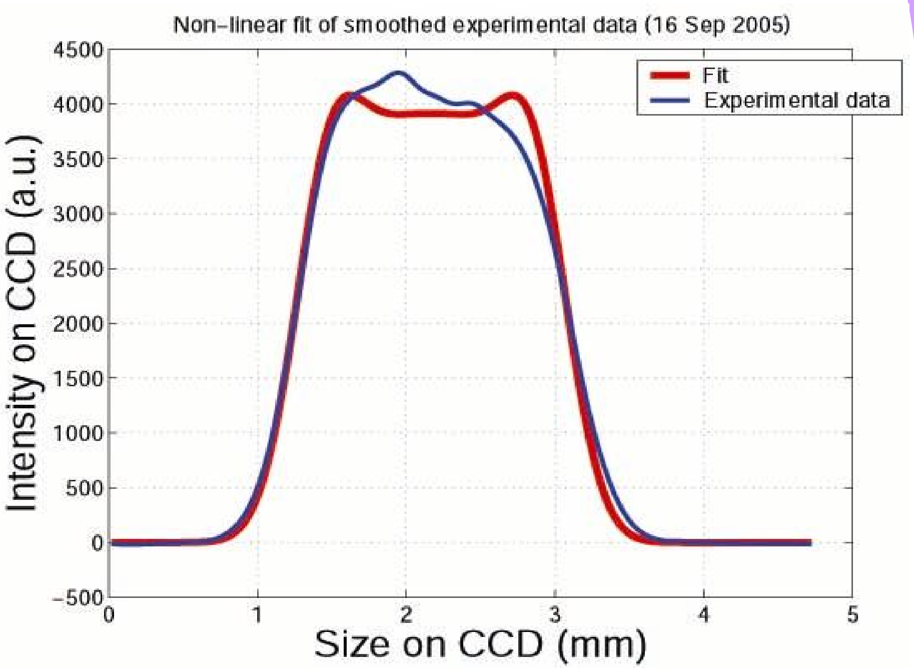


RadioShack

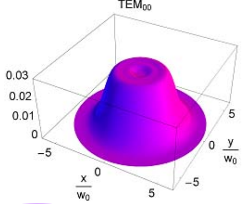


Best Mesa Beam

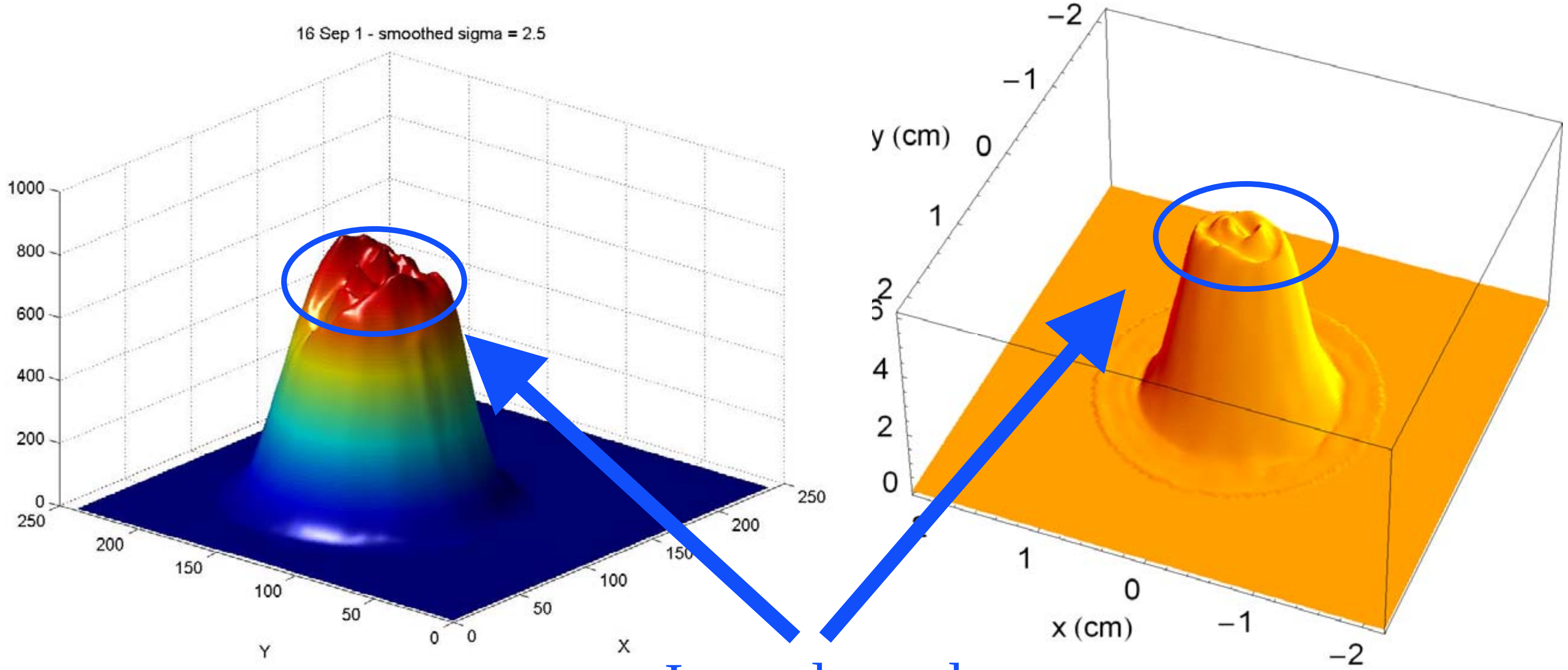




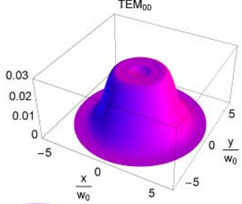
- Rsq = 0.996
- Rsq = 0.992



Best Mesa Beam



Jagged top due to imperfect mirrors

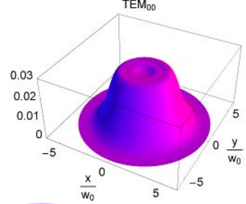


Tilt Sensitvity

- Controllability of beam is key
- Decided to first investigate tilt sensitivity
- Tilt MH mirror about a known axis

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

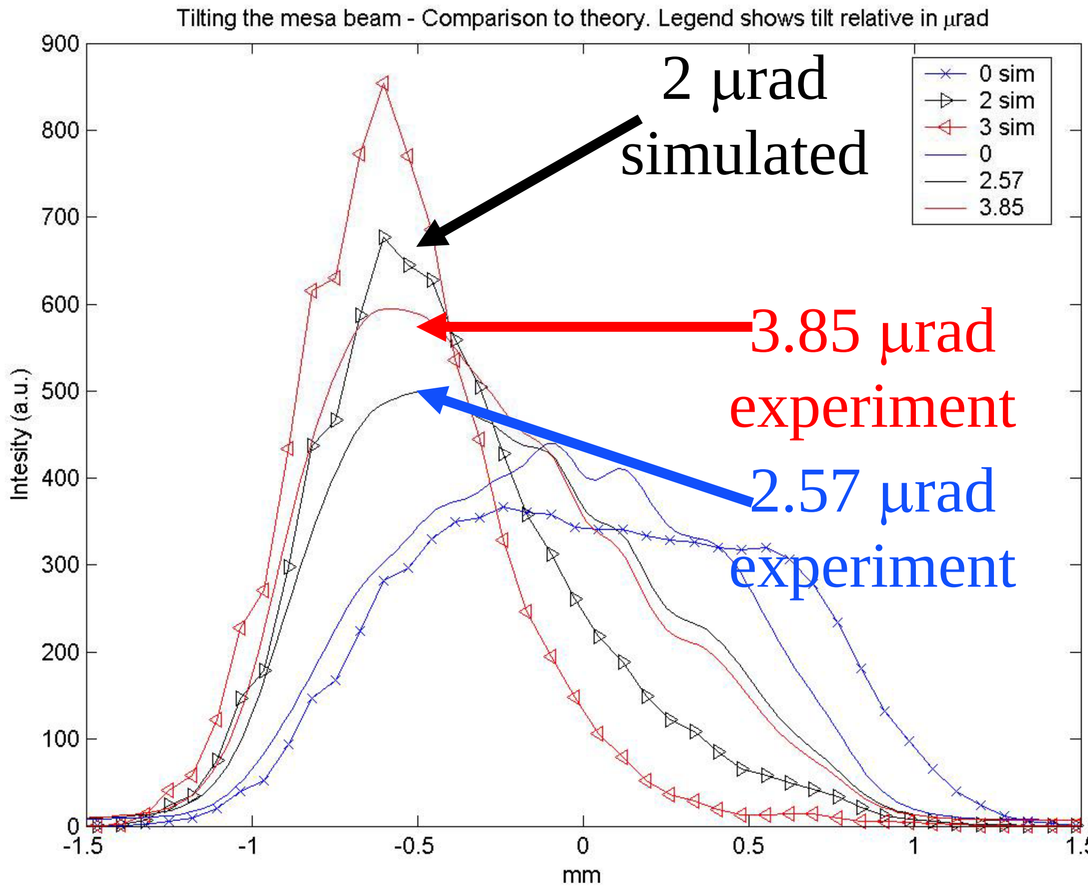
LIGO

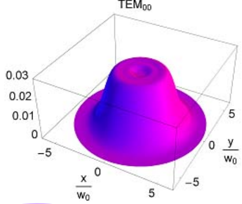


Profiles

- Profiles along axis

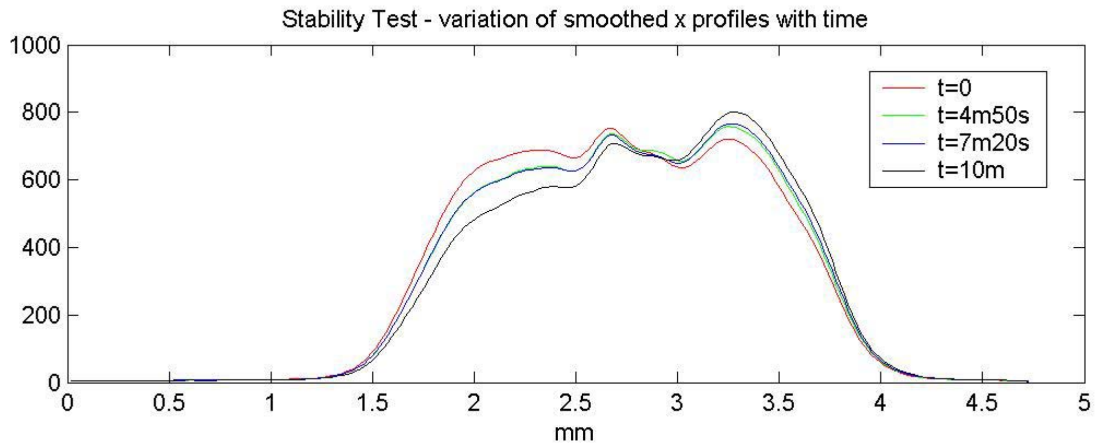
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

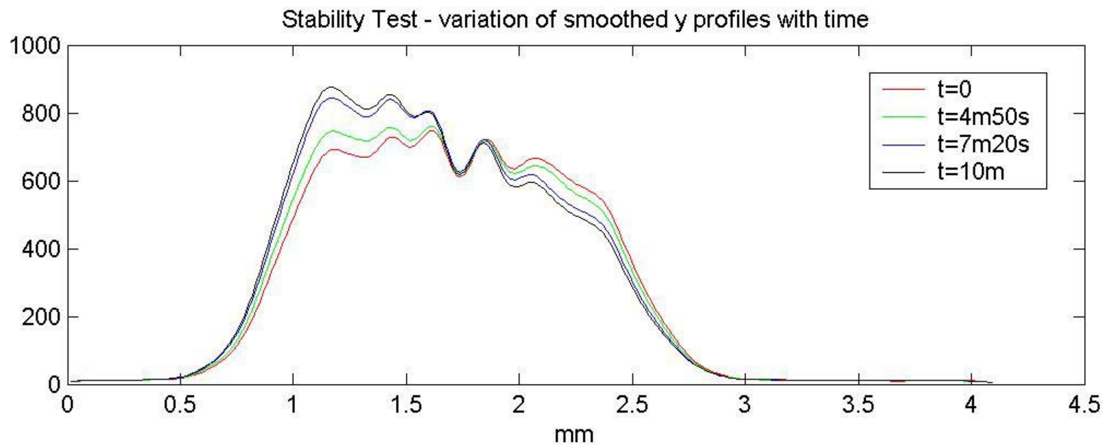


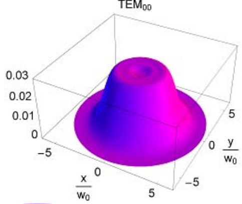


Excuses

- Lack of temporal stability
  - » vacuum?
- Stiction
- PZTs are bad



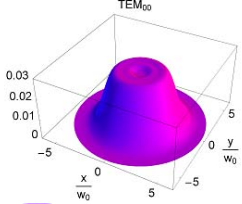




Summary

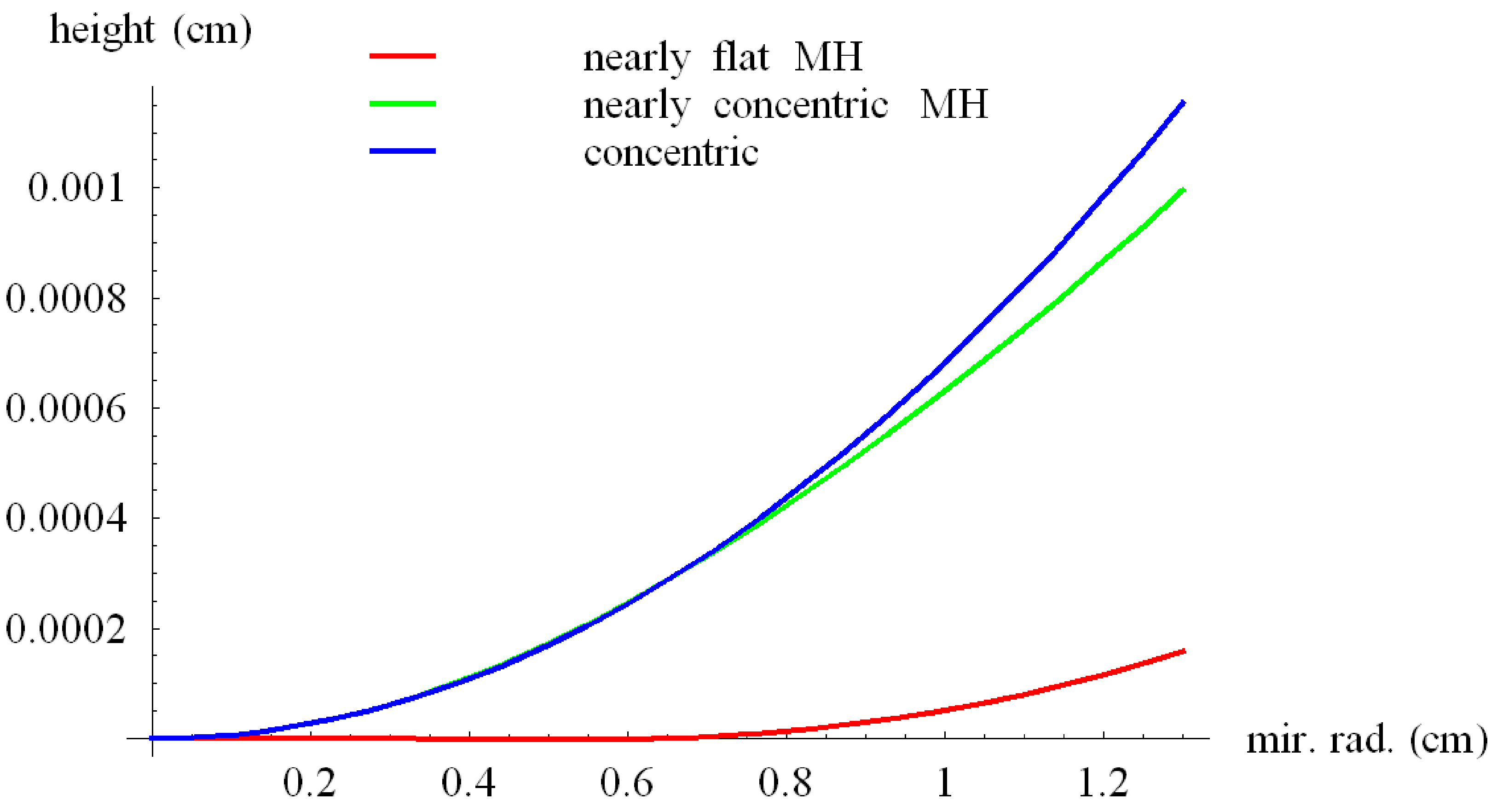
- We are able to produce acceptable flat-topped beams with imperfect optics
- We have begun to make a quantitative analysis of mesa beam
  - » Beam size appears correct
  - » Tilt sensitivity shows correct trends but less than expected by a factor of two

Further Work With This Set Up

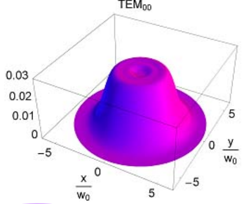


- Improve profile using new, stiffer flat mirrors
- Repeatability/ stability – vacuum operations
- Complete tilt sensitivity measurements
- Test other two MH mirrors – mirror figure error tolerances
- Long term – design and build half of a nearly concentric MH Cavity

Concentric cavity MH mirror profile



LIGO



QuickTime™ and a
YUV420 codec decompressor
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