Generation of flat-top beam in a "Mexican hat" Fabry-Perot cavity prototype for advanced GW detectors

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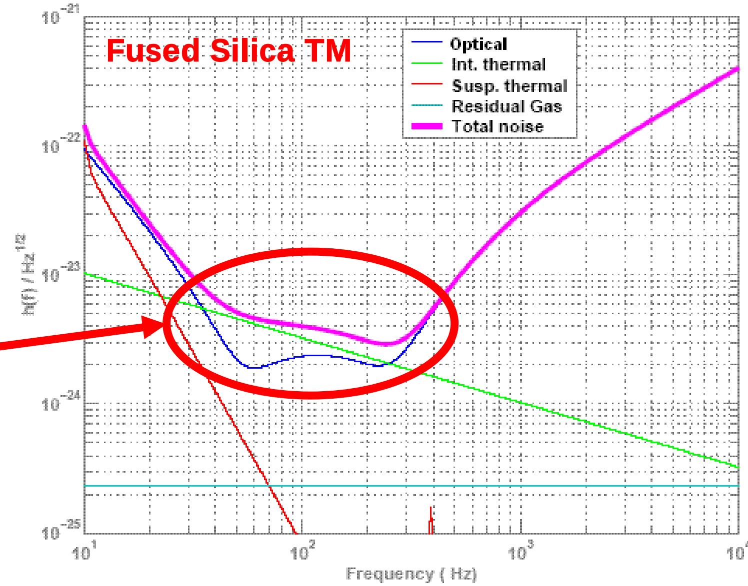
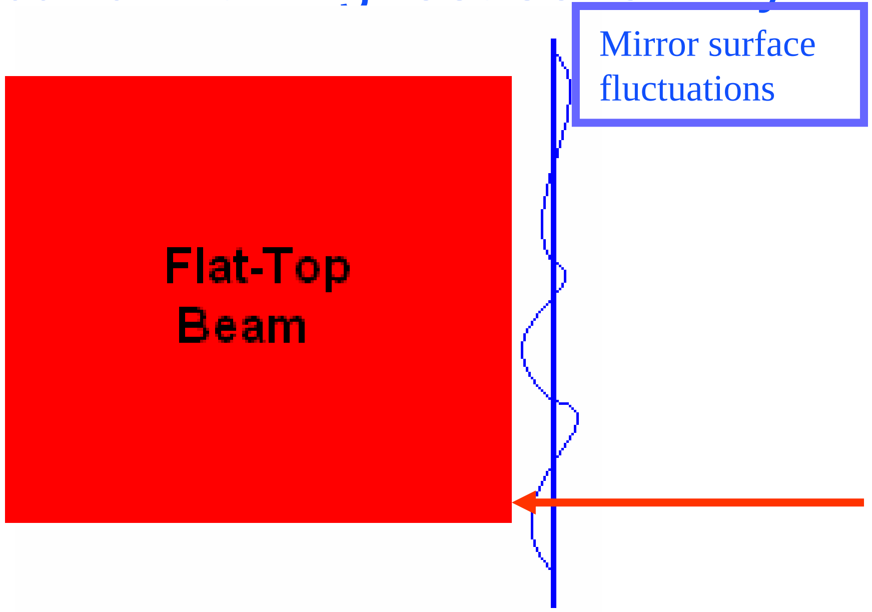
Mesa beam for advanced GWID

- Advanced GWIDs aim: sensitivity beyond the SQL
- Test mass TN will be the fundamental limit in the frequency band with highest sensitivity



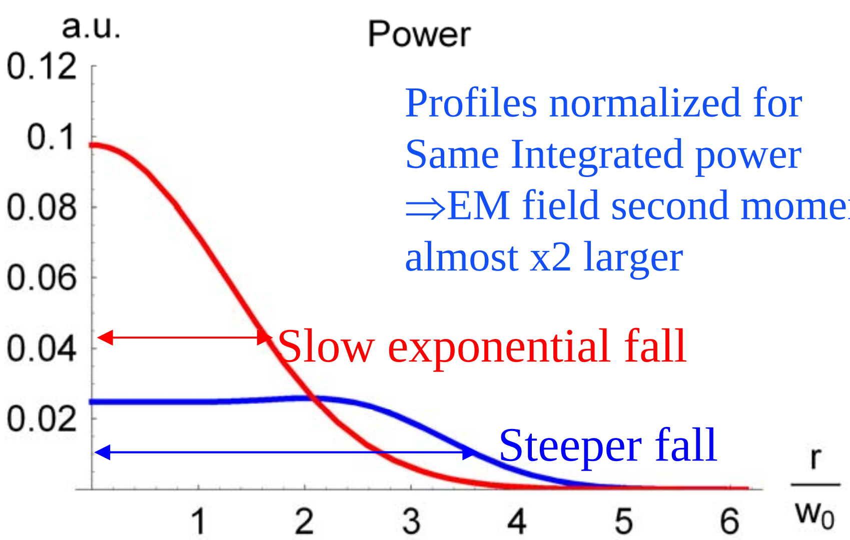


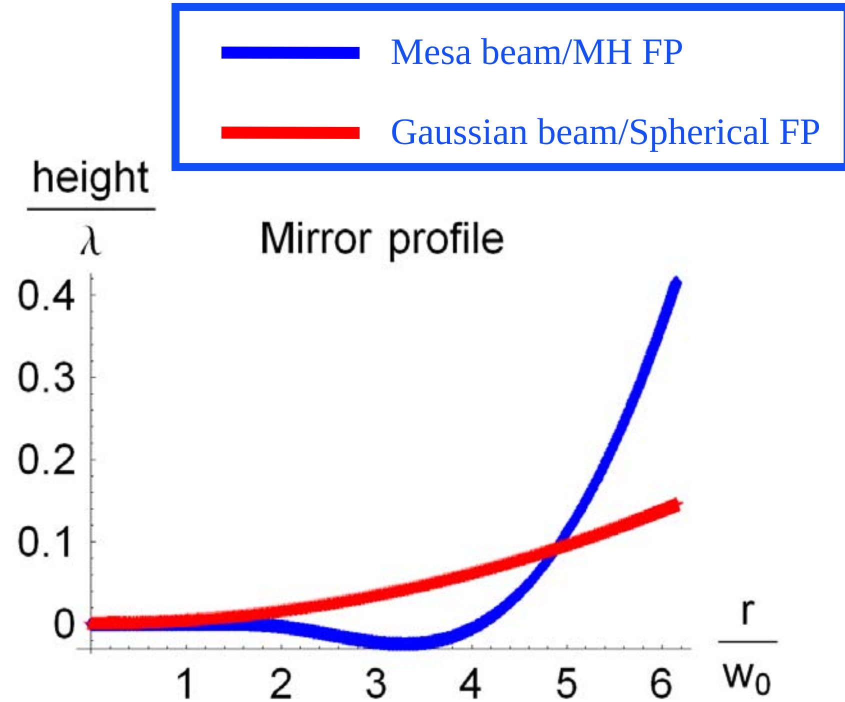
- Gaussian beams sample a relatively small fraction of the mirror surface

$\Rightarrow$ widening and flattening the light probe will depress TN

Mesa beam for advanced GWID

- It is possible to have a nearly optimal flat top beam reshaping the FP arm cavity mirrors
- The “Mesa beam” is a multi-gaussian laser field designed as superposition of minimal Gaussians with $w_0=\sqrt{(L/k)}$
- The obtained wavefront phase gives the “Mexican hat” profile to the phase graded mirror





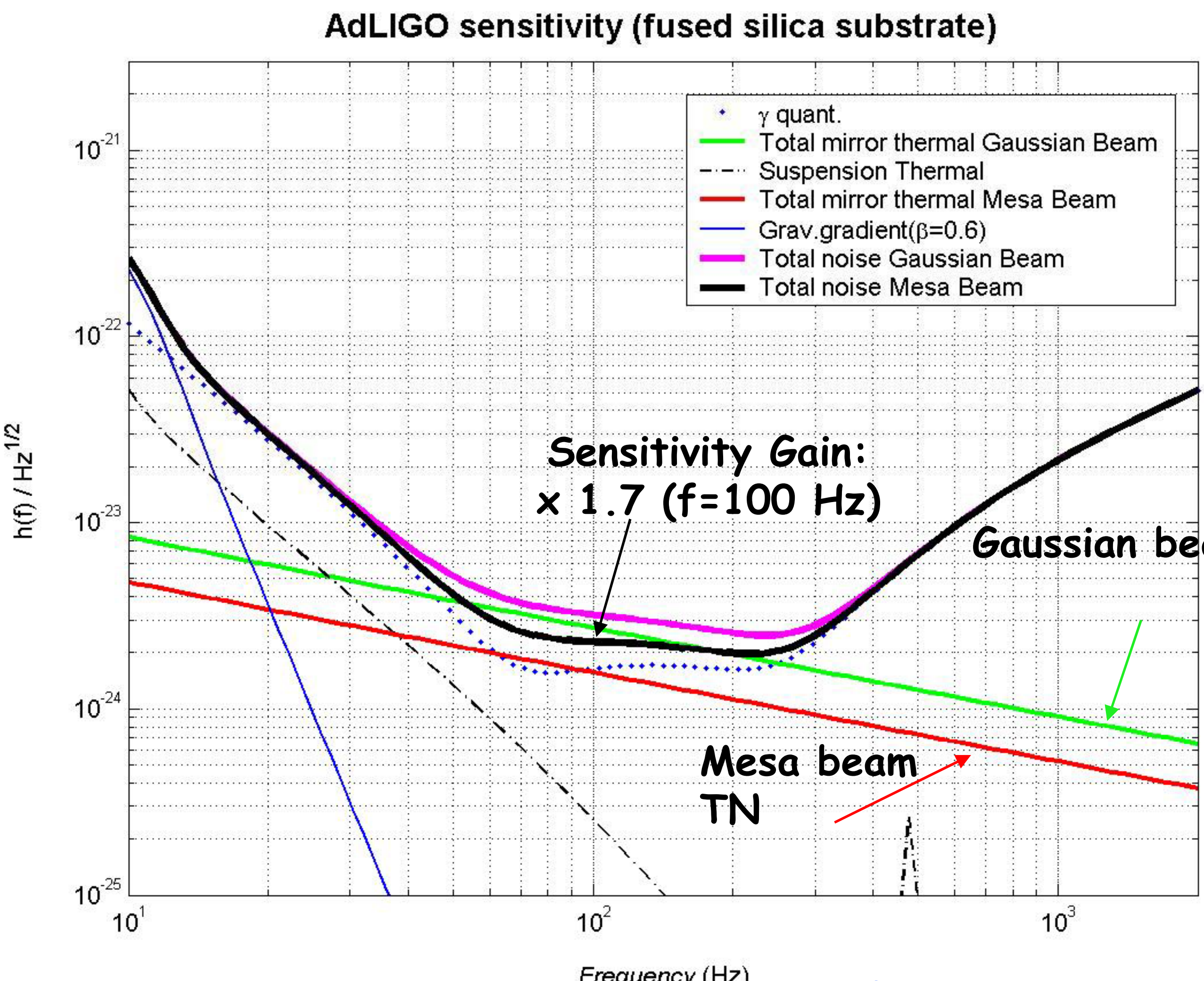
Thermal Noise Prospects

Theoretical investigations: thermal noise reduction

NS-NS inspiral Reach
193 Mpc
251 Mpc x 1.3

Detection Event Rate x 2.2

!! Mesa beam noise reduction is an **additional factor** to any other mirror development (optimized coatings, cryogeny, ecc.)

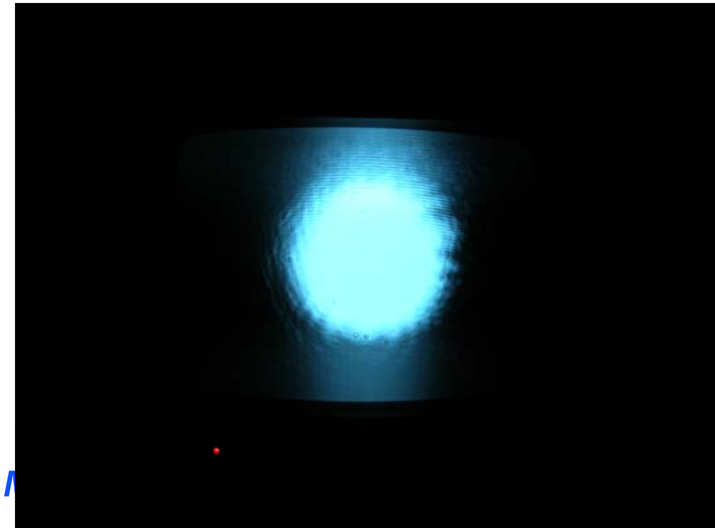


[ref. Agresti LIGO-G050310-00-R]

Mesa beam cavity prototype

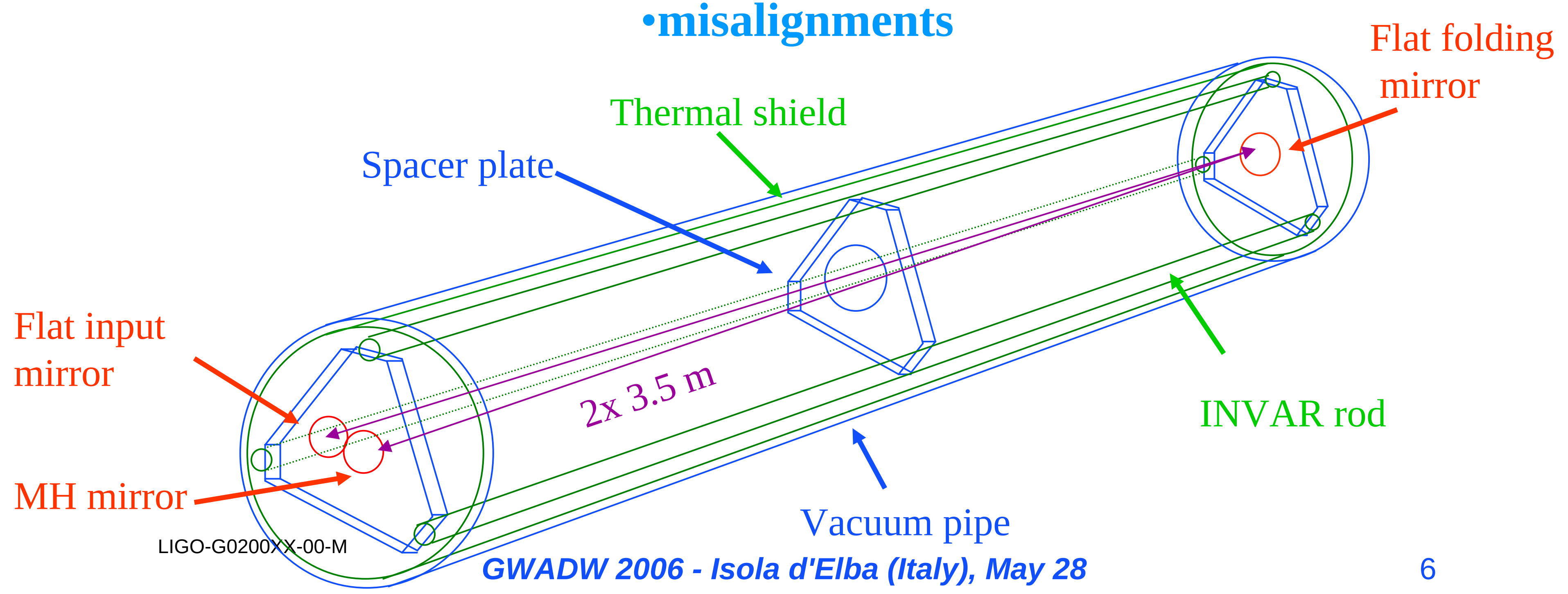
- **Experimental work** before a direct application to a GWID :

- Starting the design of a prototype to generate flat "Mesa" beams (summer 2003, Willems, D'Ambrosio, DeSalvo)
- Design and construction of a suspended rigid FP cavity at Caltech (autumn 2003 – summer 2004, Simoni, DeSalvo et al.)
- Manufacturing first test Mexican hat (MH) mirrors (2004-2005, LMA laboratory)
- Full prototype experimental set up (autumn 2004 – spring 2005, Tarallo, Willems, Agresti, DeSalvo)
- Testing MH mirrors and **achieving the first flat Mesa beam** (summer 2005, Miller, Tarallo, Willems et al.)



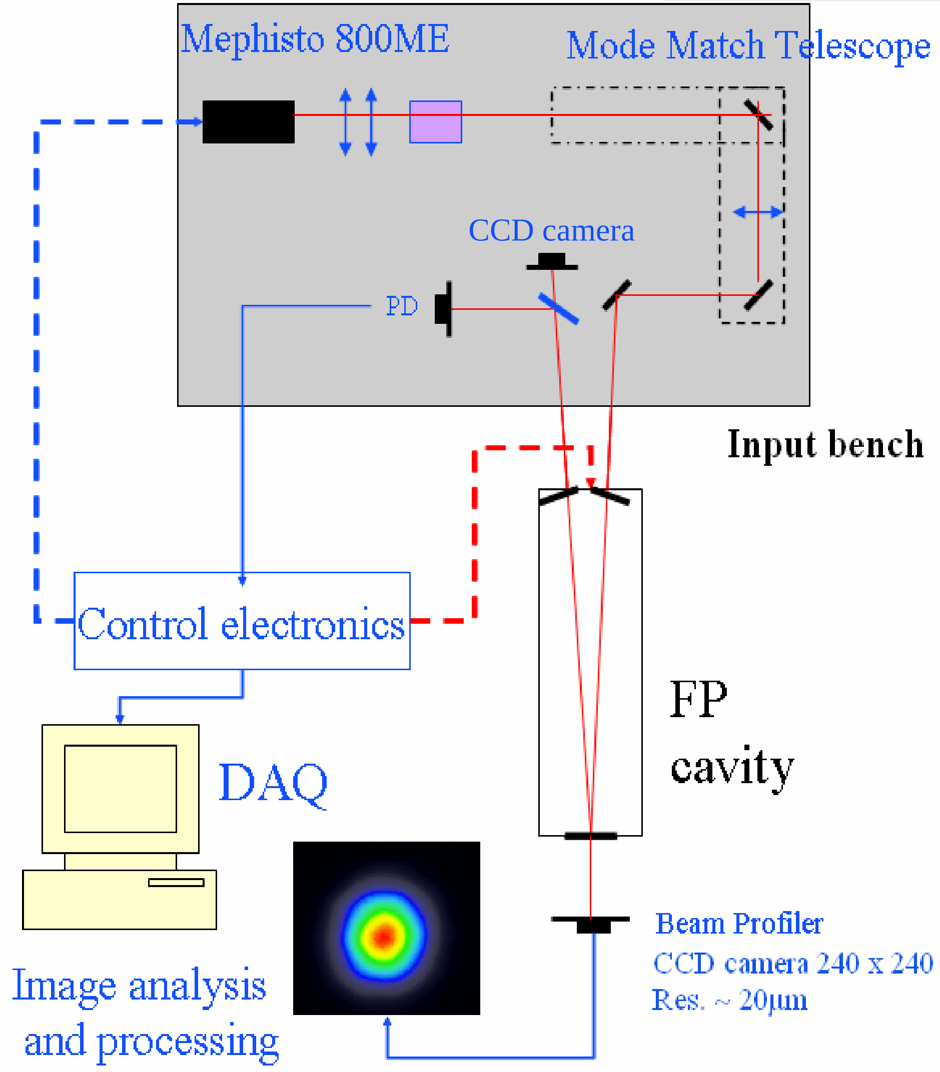
Mesa beam cavity prototype

- Necessity to verify the behavior of the mesa beam and study its generation and control before its possible application to GW interferometers
- We built a rigid, folded, suspended, 7.32m long FP cavity supporting a MH mirror to investigate the **modes structure** and characterize the **sensitivity to perturbations**
  - **mirrors imperfections**
  - **misalignments**



Mesa beam cavity experimental setup

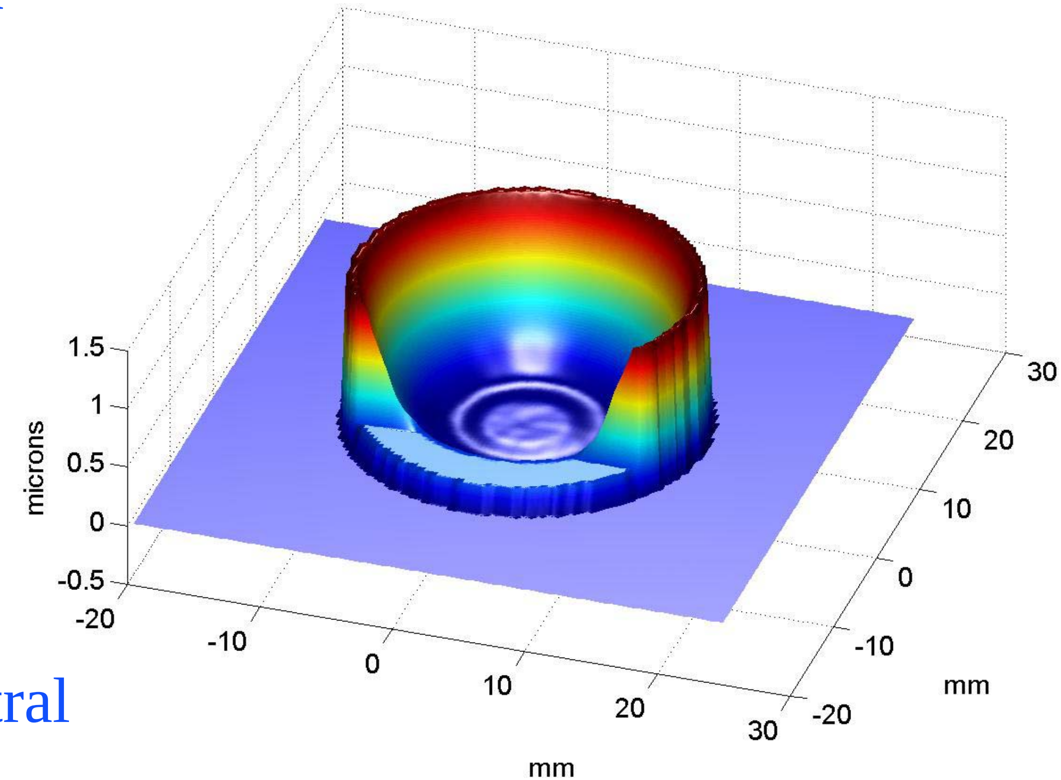
- Input/output optics bench:
- Nd:YAG Mephisto laser
- Mode match telescope
- Fast photodiode for transmitted power readout
- CCD camera to control the locked TEM
- Suspended FP cavity, F ~ 100
- Profile readout bench (CCD camera, high resolution)
- Feedback control electronics & cavity mirrors DC driving



“Mexican hat” mirrors

- LMA laboratories provided three mirror samples
- C05004 (test run):
- Thin substrate (20 mm)
- large offset on the central bump
- C05008 & C05009:
- Thick substrate (30 mm)
- Both affected with a not negligible slope on the central bump

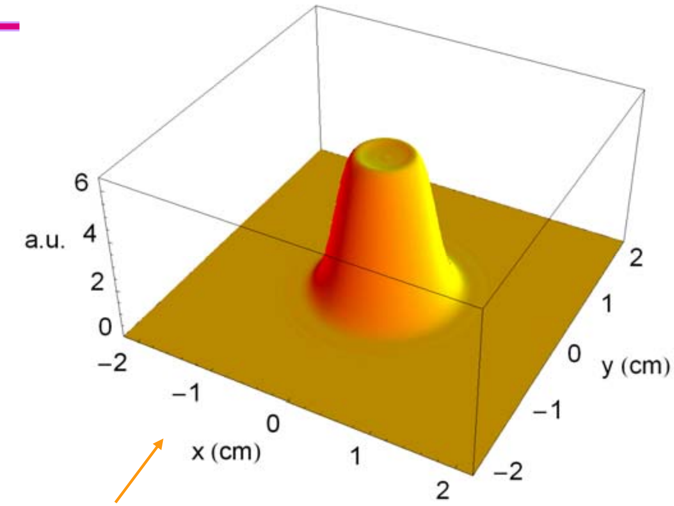
Mexican hat C05008



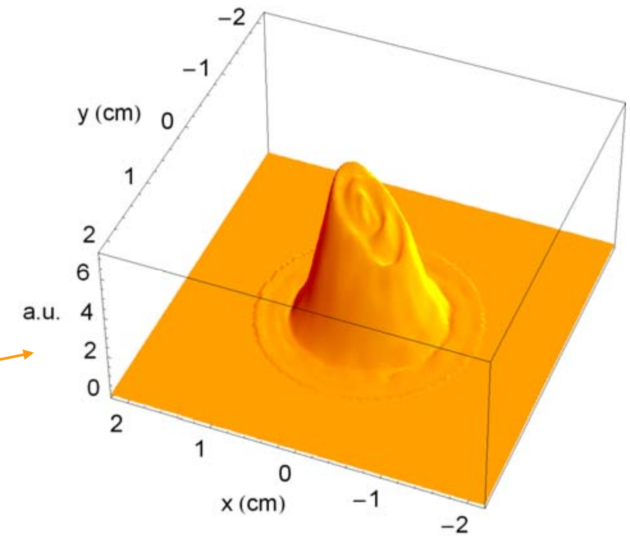
➡ We can characterize how mirrors imperfections affects the beam in such a interferometer

FFT simulations

- Using paraxial approximation, FFT codes can simulate the propagation of actual TEM patterns on optical cavities
- A Mathematica FFT routine has been dedicated to simulate our cavity beam behavior: it gave us the best tool to choose the best MH: C05008



FFT EM field on a ideal MH mirror

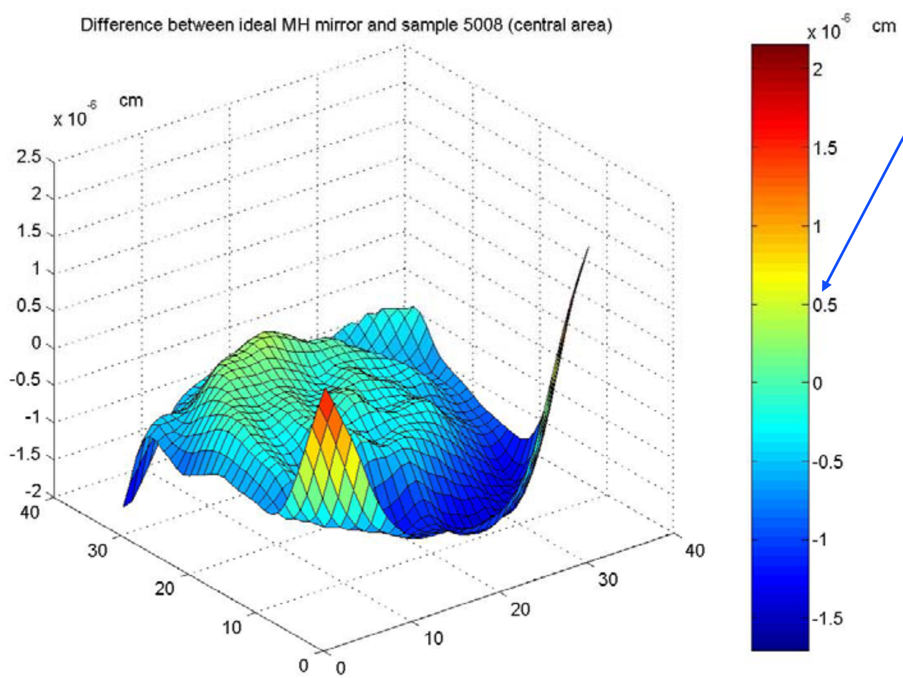


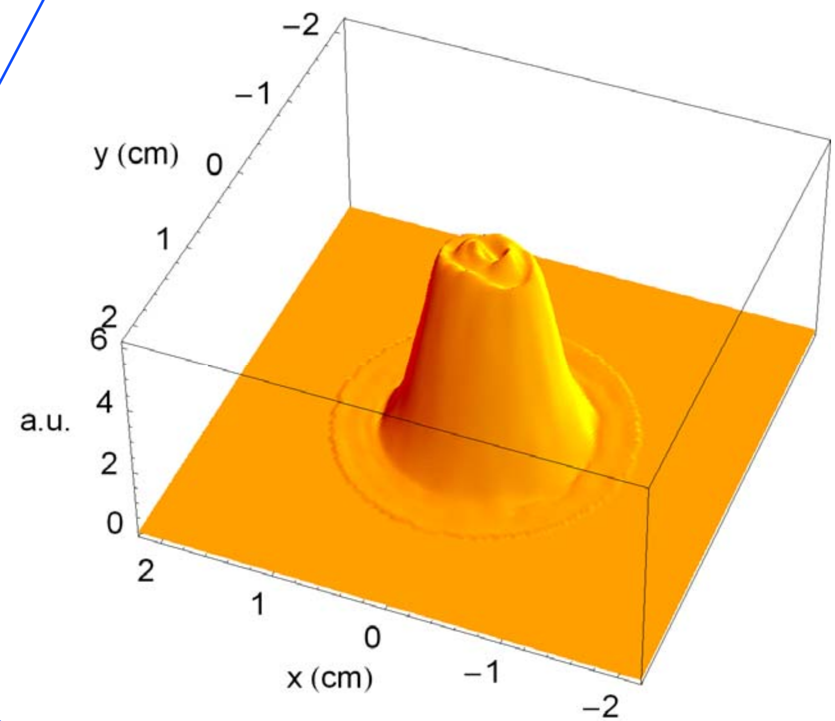
First implementation of MH C05008 map

FFT simulations

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

≈5 nm error central area





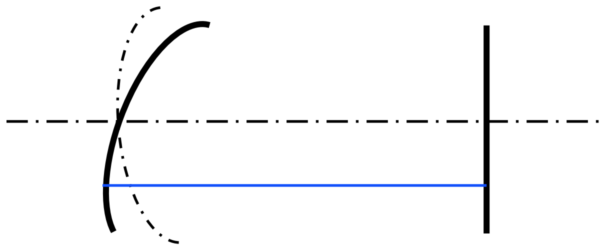
MH Cavity Alignment

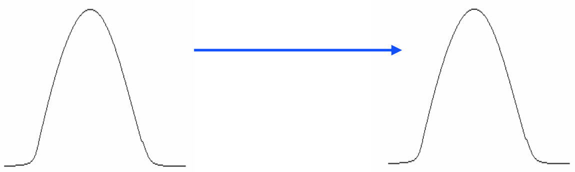
- Spherical optics: tilt is translated in a change of the optical axis
- MH mirrors: only cylindrical symmetry

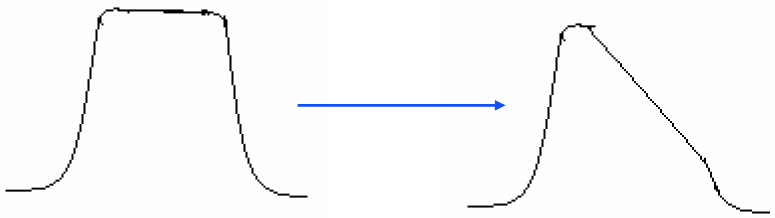
-> resonant beam phase front change with the alignment

- Folded cavity: no preferential plane for mirrors alignment

-> very difficult align within ❍rad precision

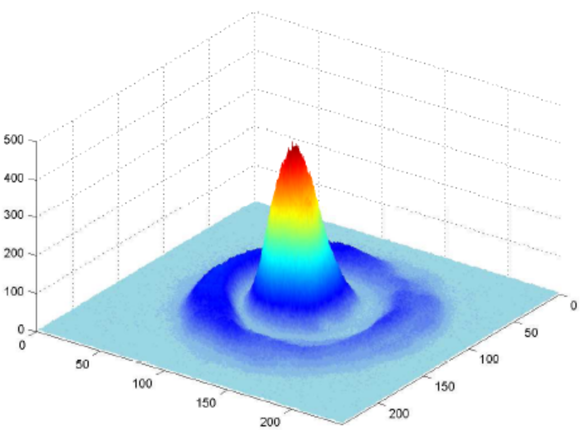




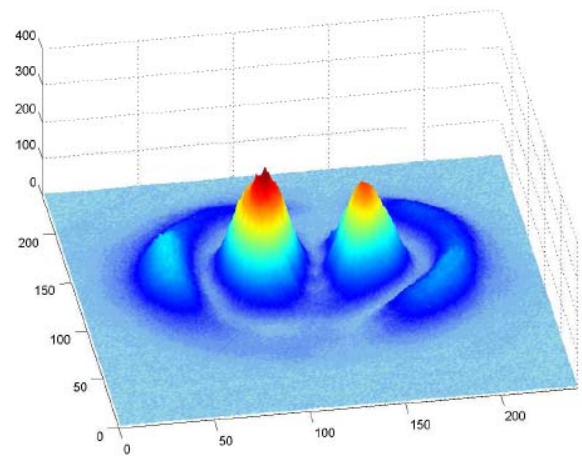


First Experimental Results

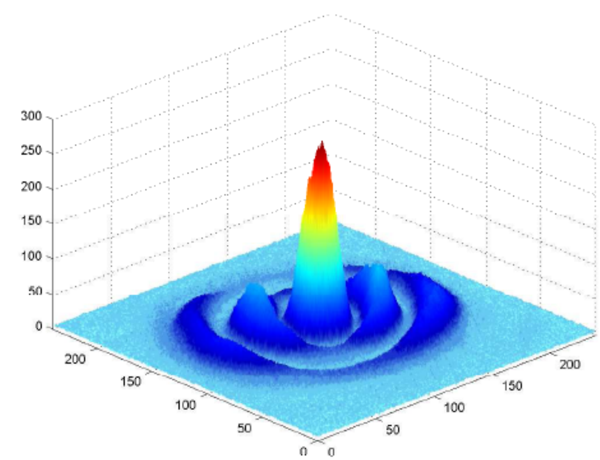
- Experimental setup (electronics, beam acquisition, locking…) tested with 8m r.o.c. spherical end mirror
- MH installation: no stable Mesa beam profile was acquired at the beginning
- Higher order modes were found very easily, good agreement with numerical prediction!



‘TEM10’



‘TEM11’

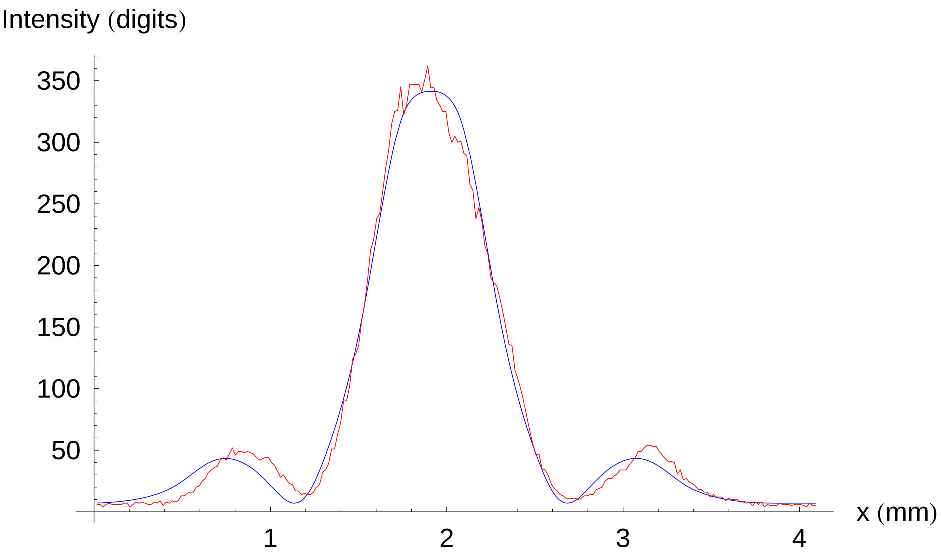


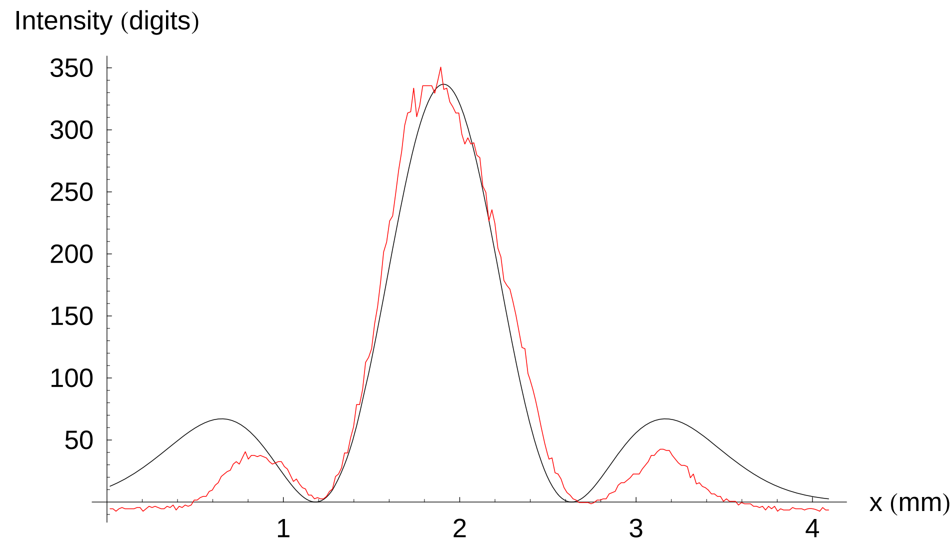
‘TEM20’

LIGO-G0200XX-00-M

First Experimental Results

'TEM10' 1D profile fit:





Fit function: Mesa 'TEM10'

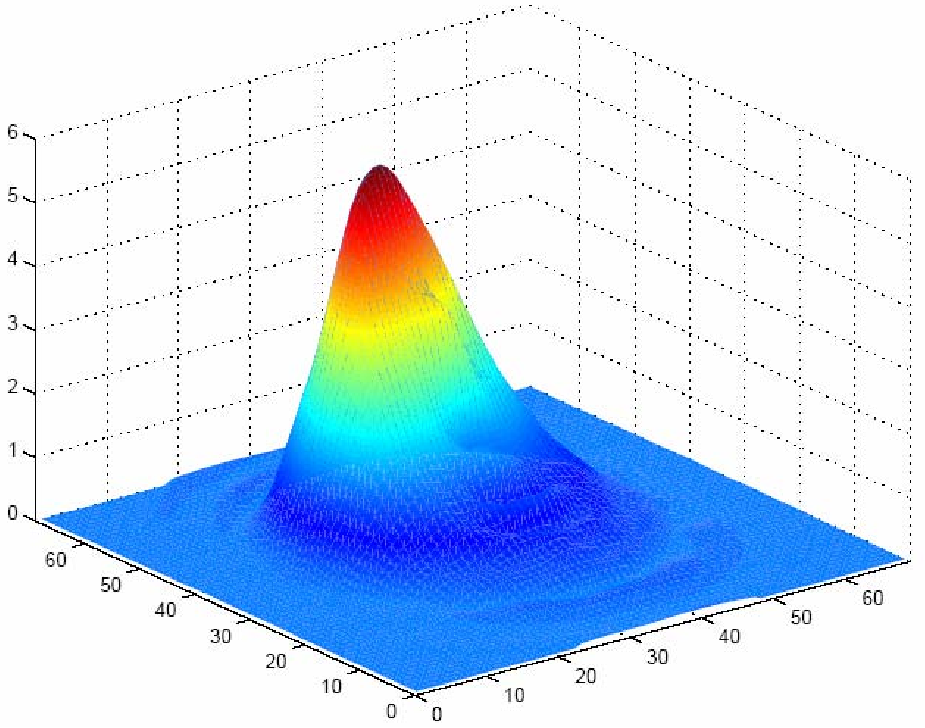
Rsq = 0.990

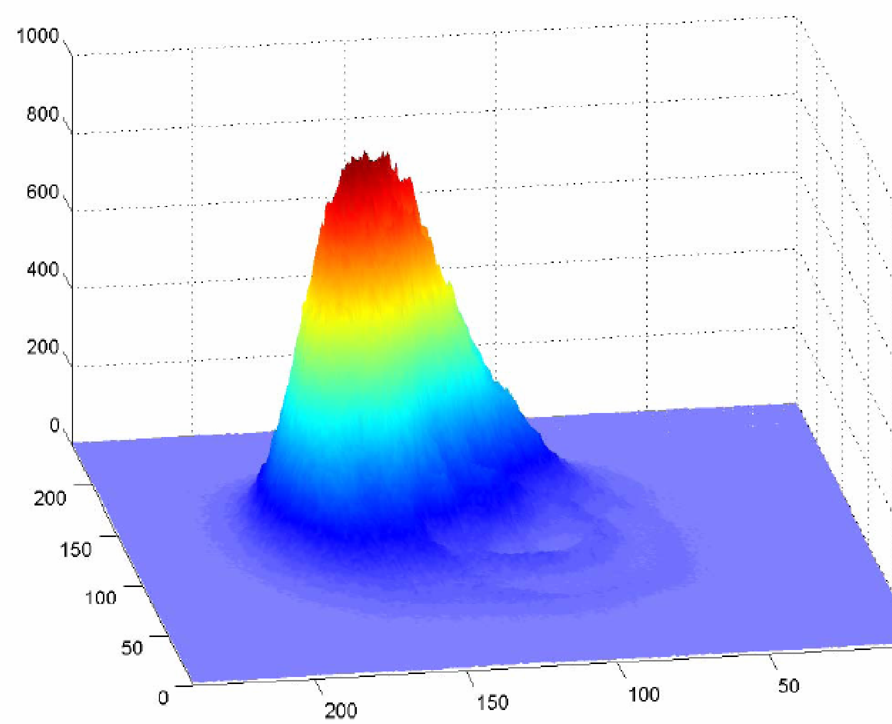
Fit function : Laguerre-Gauss TEM10

Rsq = 0.929

First Experimental Results

- Misalignments and mismatching effects has been modeled to recognize "strange" resonant modes





- TEM00 tilt simulation TEM00 data

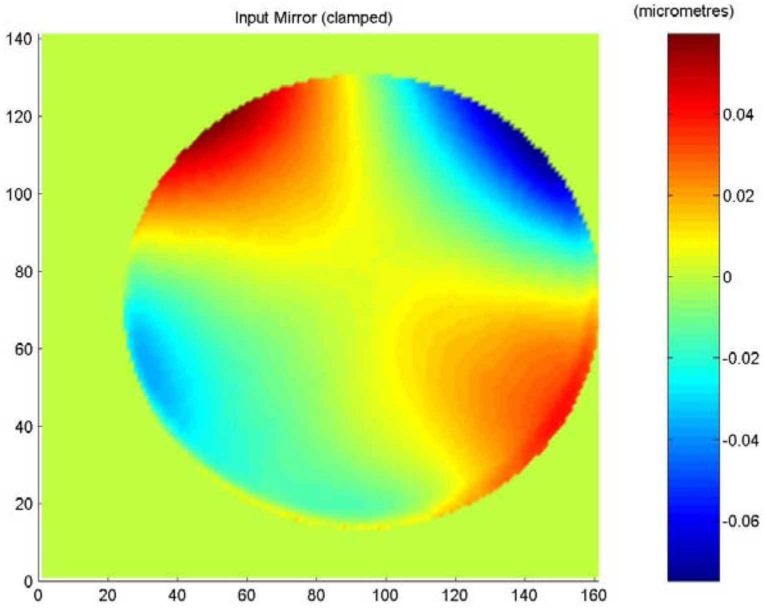
LIGO-G0200XX-00-M

Systematics and following steps

- Strange evidence: every time we tried to align the cavity, mode shapes became worse and worse (as with spherical end mirror)
- Central part of the cavity seems “unstable”: maybe the problem is not the MH but the other two mirrors

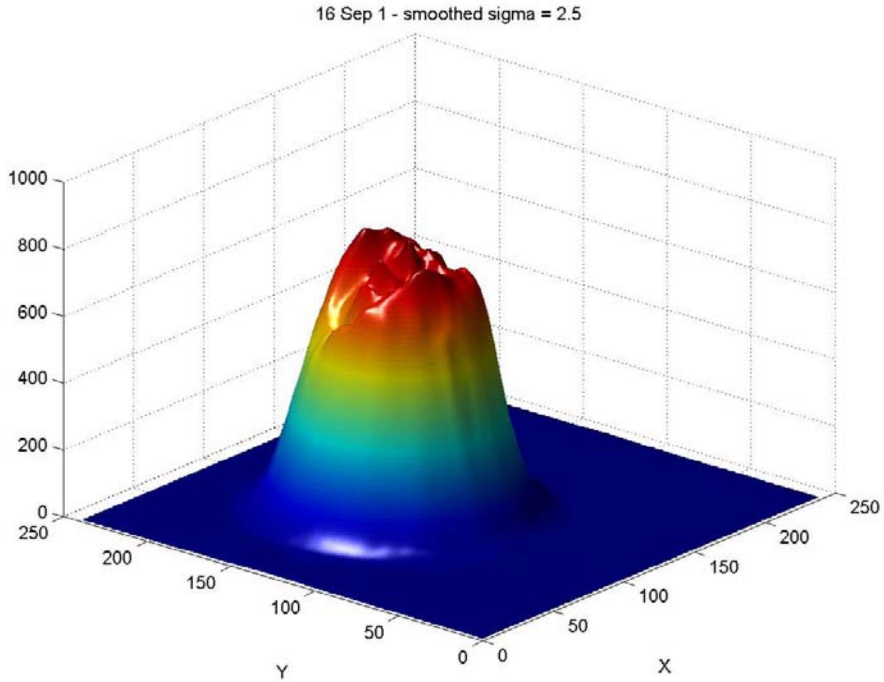
- Mechanical clamping, PZTs and screws stress ~ 60 nm deformation -> three times the height of the MH central bump

- We changed mirrors mounts reinforcing flexible mirrors with aluminum rings

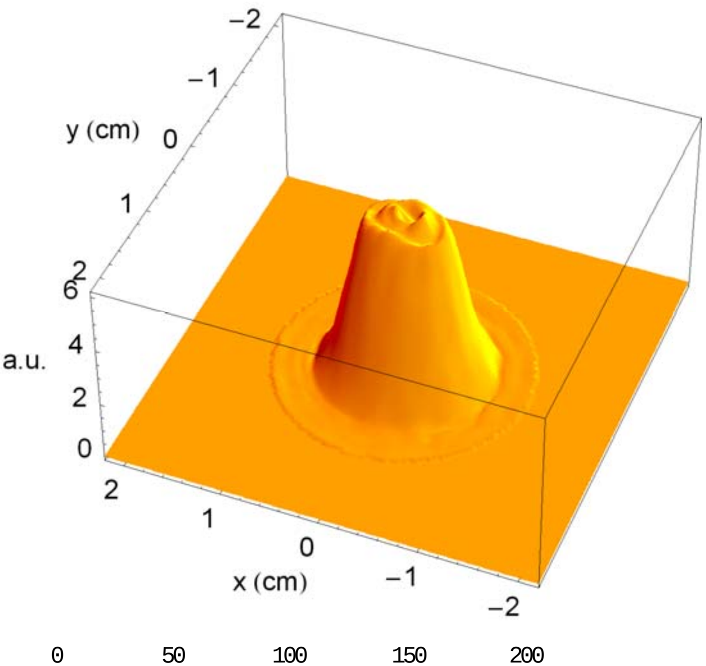


First Mesa beam observations

- We were able to stably lock on the Mesa ‘TEM_{00}’



Best Mesa beam

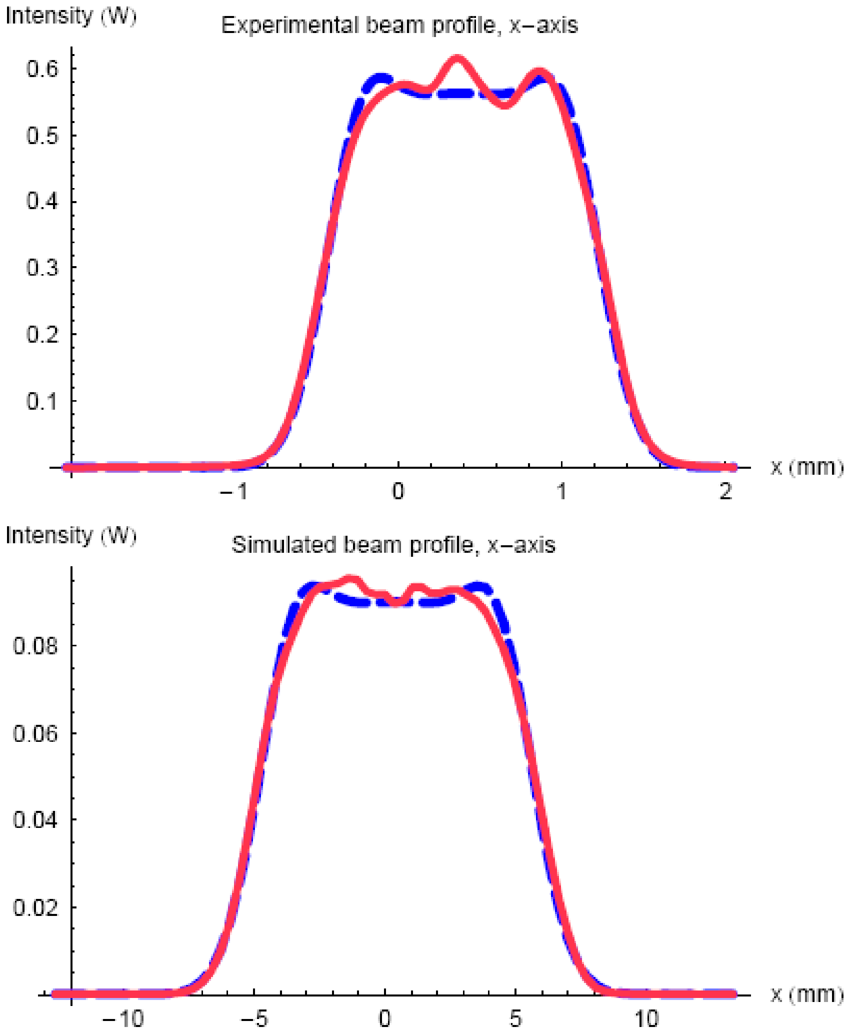


CCD Density plot

The result is consistent with the best achievable using our current prototype MH mirror

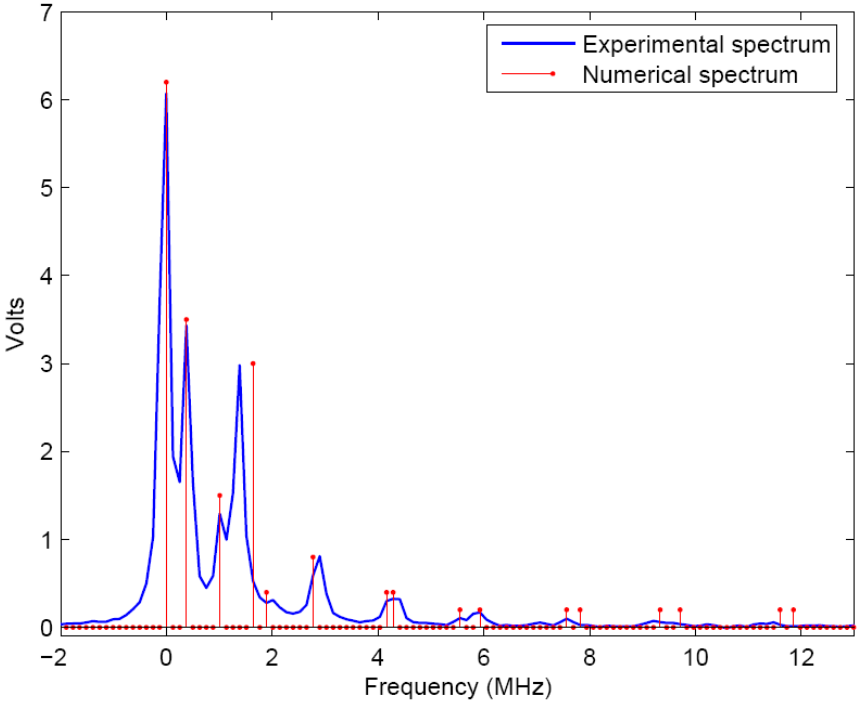
First Mesa beam observations

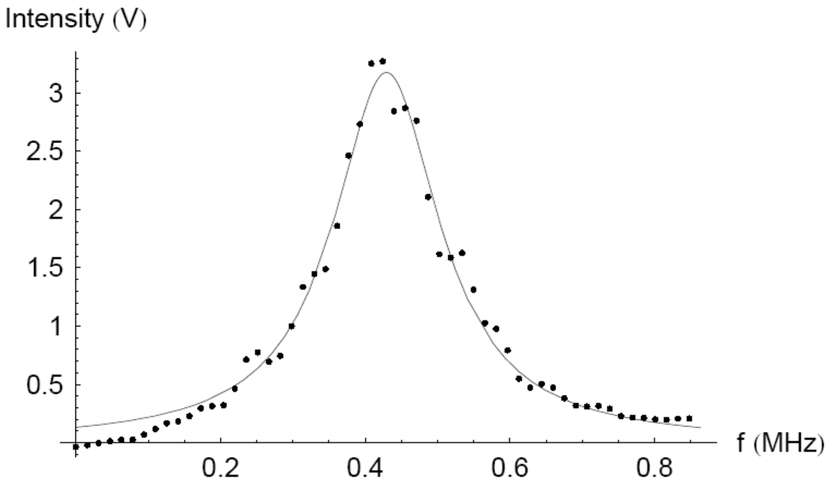
- Comparison with FFT results:
  - Jagged top due to MH bump imperfections both in FFT and in experimental profiles
  - Deviation from the ideal Mesa field, almost the same
  - Still same asymmetry due to flat mirrors imperfections
  - The beam has the expected size within the experimental uncertainty
- Input and folding mirrors are the second main limitation



MH cavity characterization

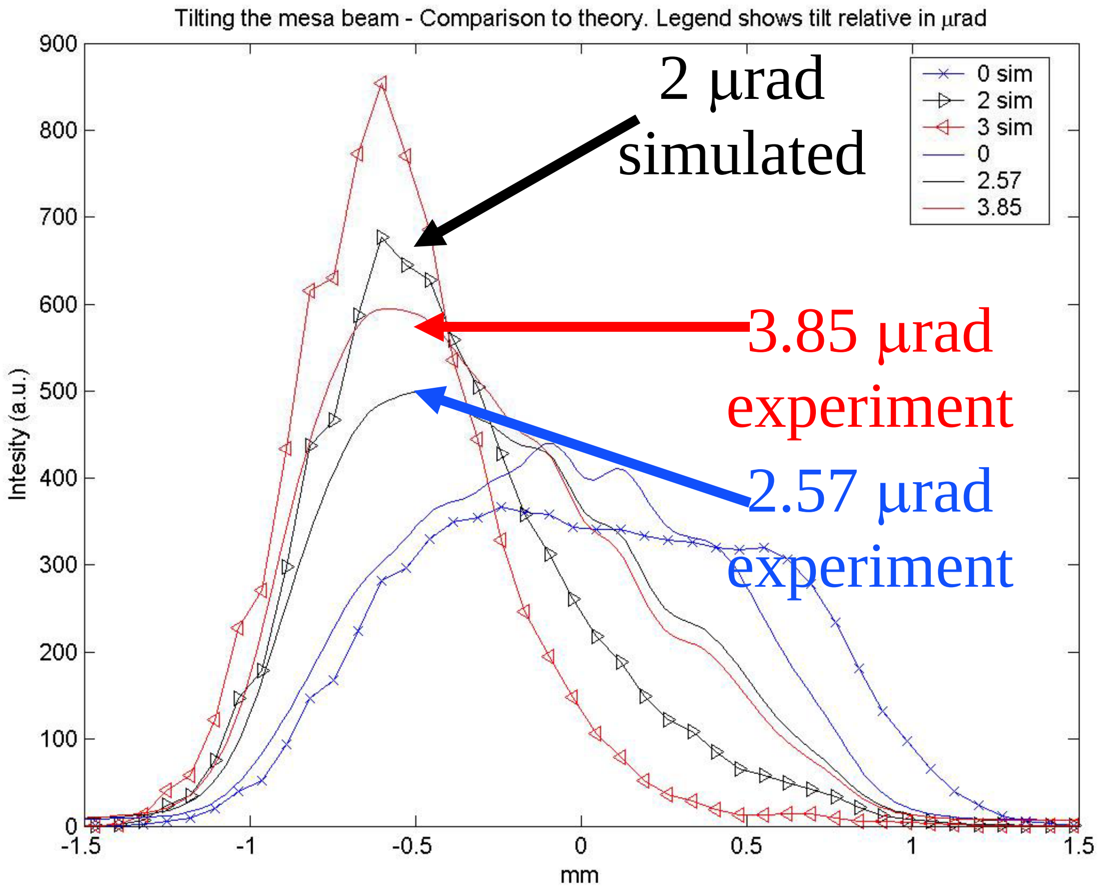
- Remarkable agreement between numerical eigenvalues and experimental spectrum
- Cavity finesse and coupling are unavoidable depressed by flat mirror deviations ($F_{exp} \leq 68$ instead of 100)





Tilt sensitivity

- A preliminary quantification of beam sensitivity to mirror tilts was carried on
- Simulations and experimental data shows the same trend but a factor 1.5 of disagreement (TBI)



Conclusions and Future

- We are able to produce acceptable flat-topped beams with imperfect optics
- Alignment more taxing than with spherical mirrors
- MH “profile deposition” technique is actable, but better for larger mirror radius
- Next steps:
- Study MH FP coupled with recycling cavities
- AdLIGO and future high power detectors: nearly-concentric configuration (MHC $\frac{r^2}{2L} - h_{MH}(r)$)
  $\Rightarrow$ A new 120m interferometer prototype (EGO?)