LIGO *Core* Optics:

a decade of development and experience

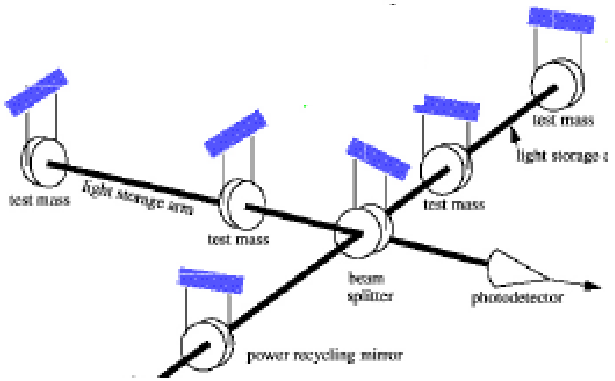
W. Kells

LIGO Laboratory, Caltech

With acknowledgement of entire LIGO team for its optical development

LIGO "Core" Optics

- 6 (4 test masses; splitter; recycling mirror) large ϕ optics which form high power cavities.
  - » 11Kgm (ϕ 25cm, h 10cm)
  - » Low loss, low distortion fused silica



- Designed (epoch '94-97) to achieve science requirements: with 6Watt input
  - » Extensive simulations
  - » Protracted "pathfinder" fabrication test pieces
  - » Transition from 535 to 1064nm
    - – Valuable lessons learned from Caltech 40m prototype interferometer

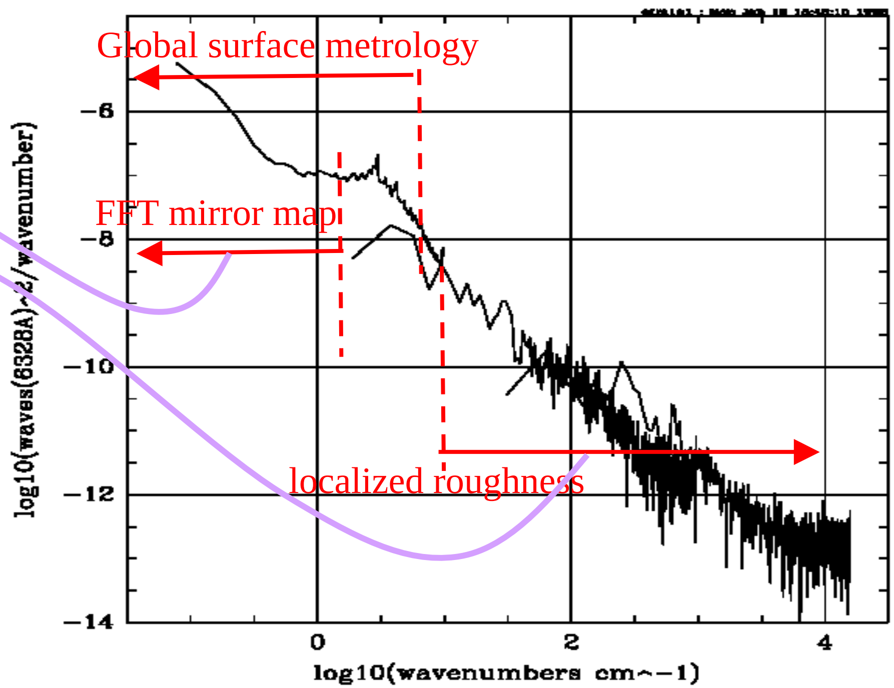
Major early concerns

- Fabrication tolerances: match of optical modes
  - ≈ Δ ROC of mirrors ⟹ arm imbalance: excessive “contrast defect” to dark port
  - ≈ Δ reflectivity, loss
  - » Coating stability and uniformity
- Thermal lensing: effect on recycling cavity “point design”
  - » Long term contamination build up on HR surfaces
  - » Uncertain residual Silica bulk absorption.
- Static charging on suspended dielectric TMs
- Inherent unstable recycling cavity design
  - » Hypersensitivity to polish, coating, homogeneity errors
- Effective loss of long cavities with figure distortions
  - » Essential target of “FFT” studies
  - » Coupled with coating reflectivity tolerance: $\mathbf{r_{ifo}}$ **>/< 0** (point design recycling)

Optical Loss Expectations

- Goal: $G_{RC}^{CR} \geq 30$ based on older polish/coating information
- Pathfinder development & fabrication proved much better:
  - » Micro roughness σ_{rms} <0.28 nm $\Longrightarrow$ prompt loss $\sim(4\,\pi\,\sigma_{rms}/\lambda)^2$ < 10 ppm
  - » Super polished substrate 2 - 3x lower σ_{rms}

- Simulation (FFT) with Fab. Data:
  - Figure= modal distortion
  - Roughness= loss
  - Low absorption= cold "start up"
  - Witness sample reflectivity

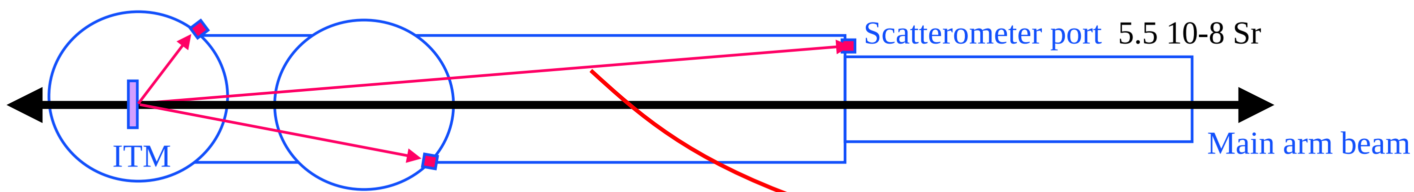


Simulated G** (at least: CR field not affected by degenerate recycling) **far exceeds goals

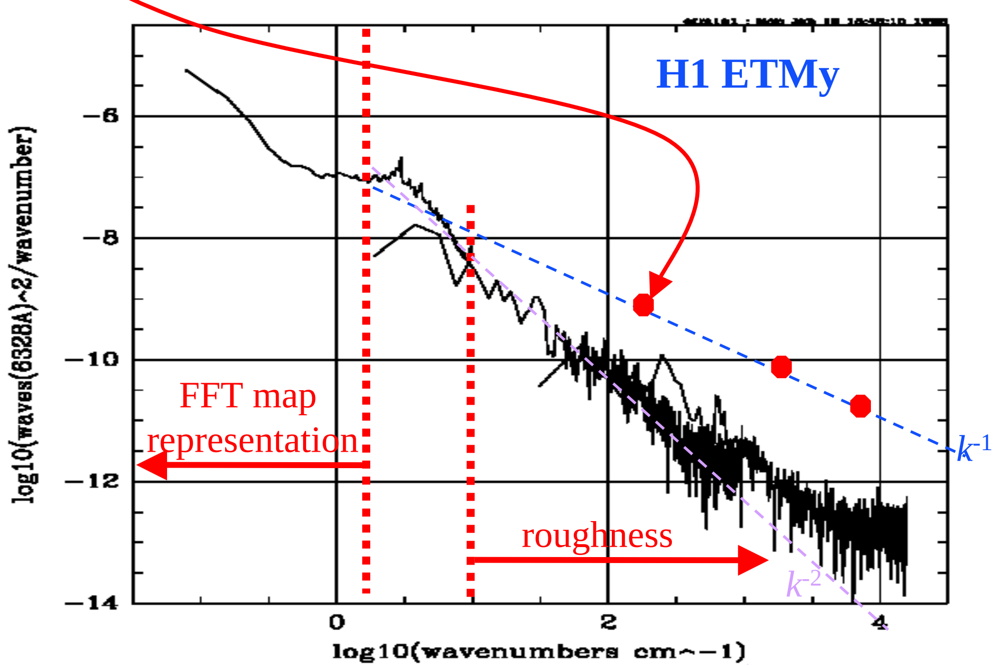
- **Consistent with Advanced ligo requirements**

Scatterometer studies

- Observed interferometer gains lower than Sim. predictions.
  - Consistent with 50-70ppm avg. additional loss per TM.
  - Consistent with “visibilities” (resonant reflectivity defect) of individual arms
- In situ studies: Some HR surfaces viewable @ 3 angles:



- Angular dependence more isotropic, “point like” than metrology prediction



- In situ observed scatter ~70 ppm mirr
- ~same level, character for every TM independent of history/cleaning.

In Situ Optics Performance

- G_{RC}^{CR} ~41, which is:
  - » Consistent with measured arm visibilities
  - » Consistent with total arm loss dominated by prompt scatter.
  - » Scatterometer data extrapolated to absolute loss

Replaced ITM

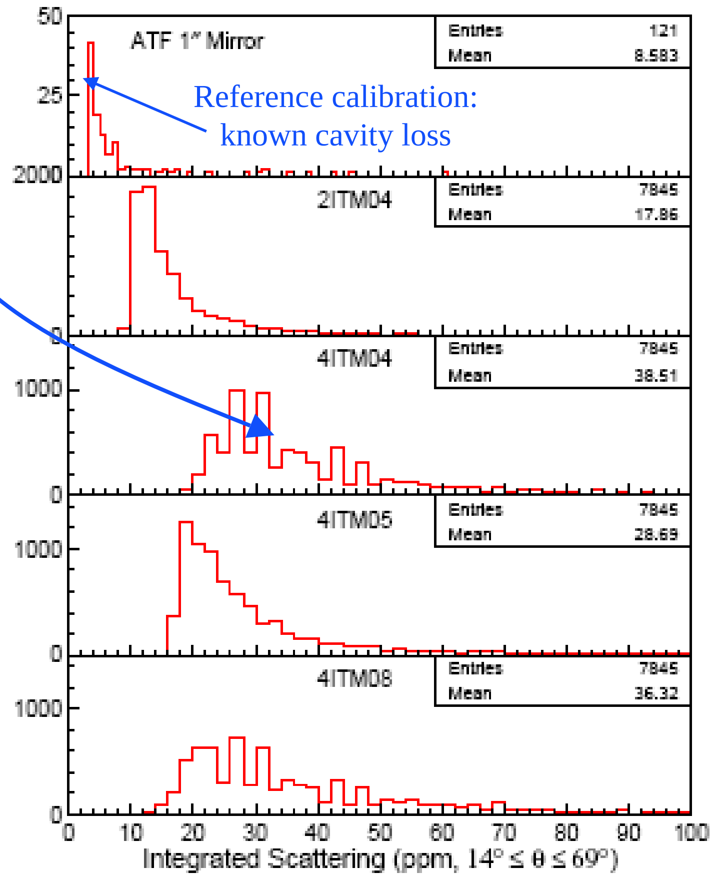
CAVITY	V	T_{ITM}	$T_{WITNESS}$	Scatter
2k X	.0222	.0277	.0283	0.85
2k Y	.0211	.0272	.0281	7
4k X	.0241	.0279	.0275	7.5
4k Y	.0214	.0263	.028	8.8

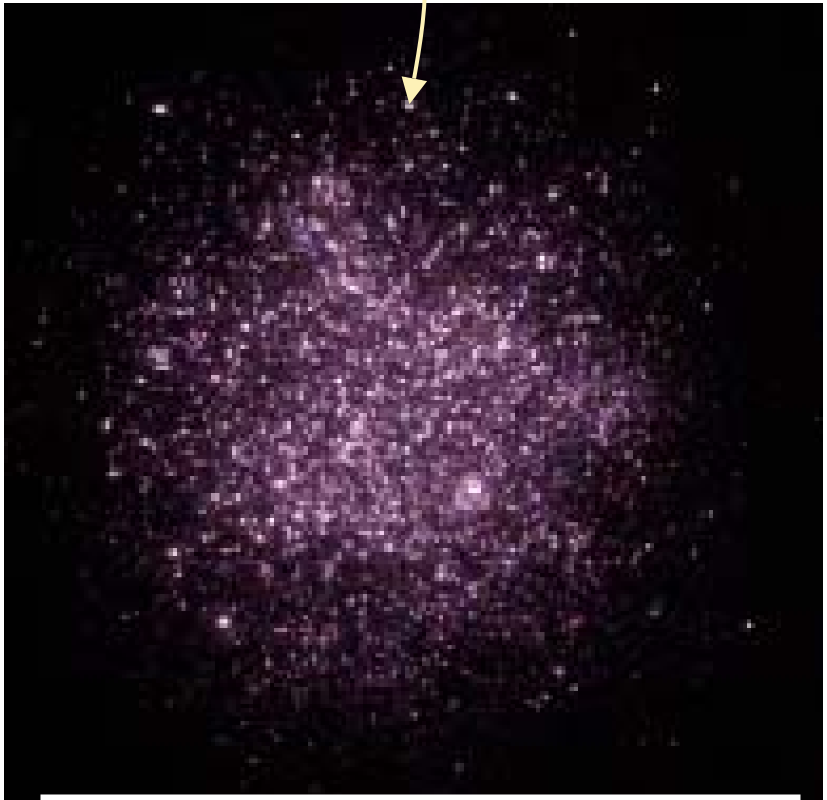
  - » Consistent with lower than anticipated contrast defect (and small FFT dependence on maps)

Homogeneous roughness ?

- Expect isotropic glow from "homogeneous" polish roughness
  - » Find: "point" defect scatter dominates
  - » Bench scans (1064nm) also show excess

Is it just dust ??

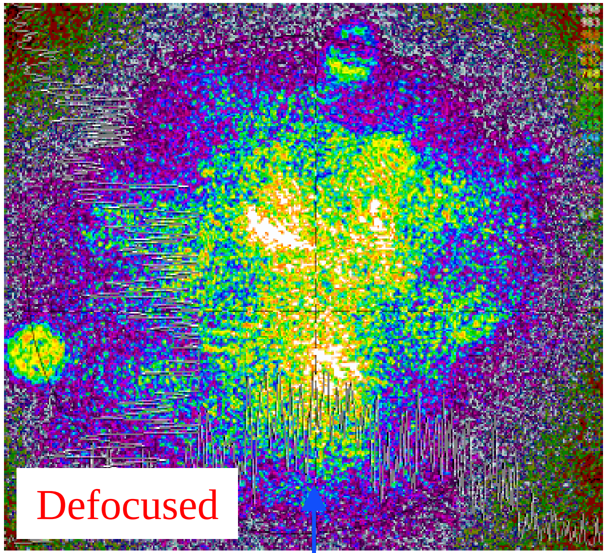


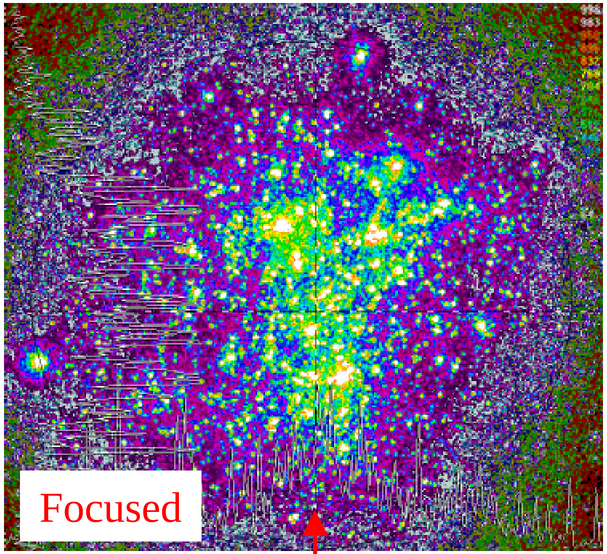


Resonant arm, Gaussian illuminated ETM

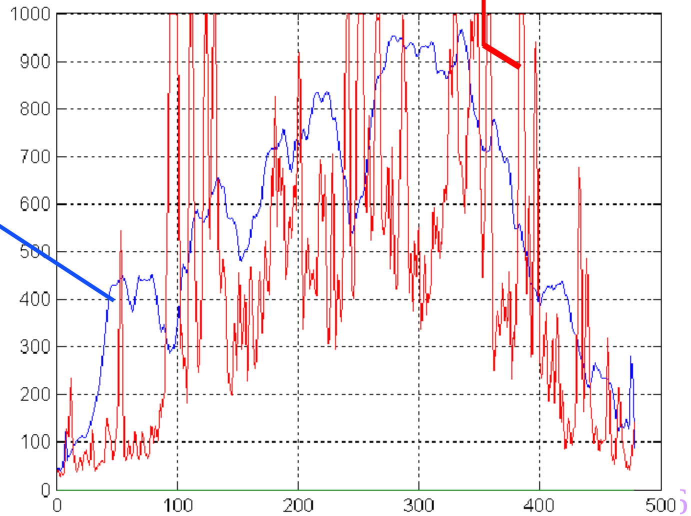
Analysis of the "Globular Cluster"

- Cleanest point scatter image: 2k ETMy:
  - » Grab video stills for detailed analysis:



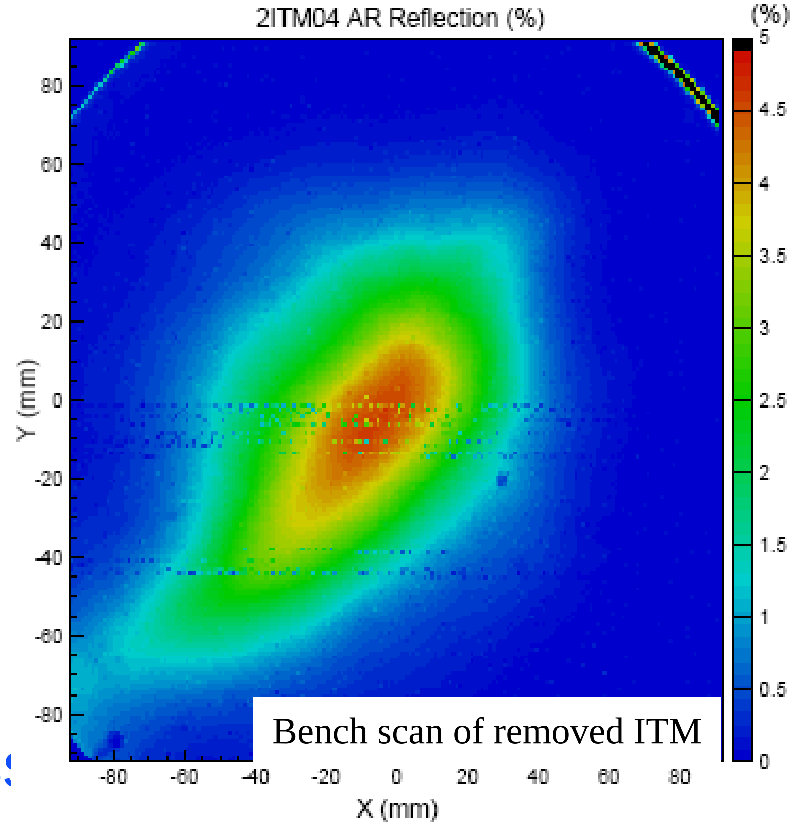


- ➢ This point defect background ~same for all optics.
- ➢ Diffuse (micro roughness) background contributes < 1/3 of total scatter.
- ➢ Other blemishes don't dominate total (?)
- ➢ Puzzle: Why these point defects missed in Lab. QA?



Coatings sensitive to handling

- For several years Hanford 2k performed poorly
  - » X arm visibility (resonant reflectivity) poor
  - » Ugly recycling cavity "mode" pattern
  - » Excess dark port contrast
  - » More dramatic: unlocked arm cavity $|r| \neq 1$



- Found: AR coating anomaly
  - » Hypothesis: extended harsh cleaning of surfaces had etched coating layers.

Lesson: coating sensitivity to thickness change (confirmed by model).

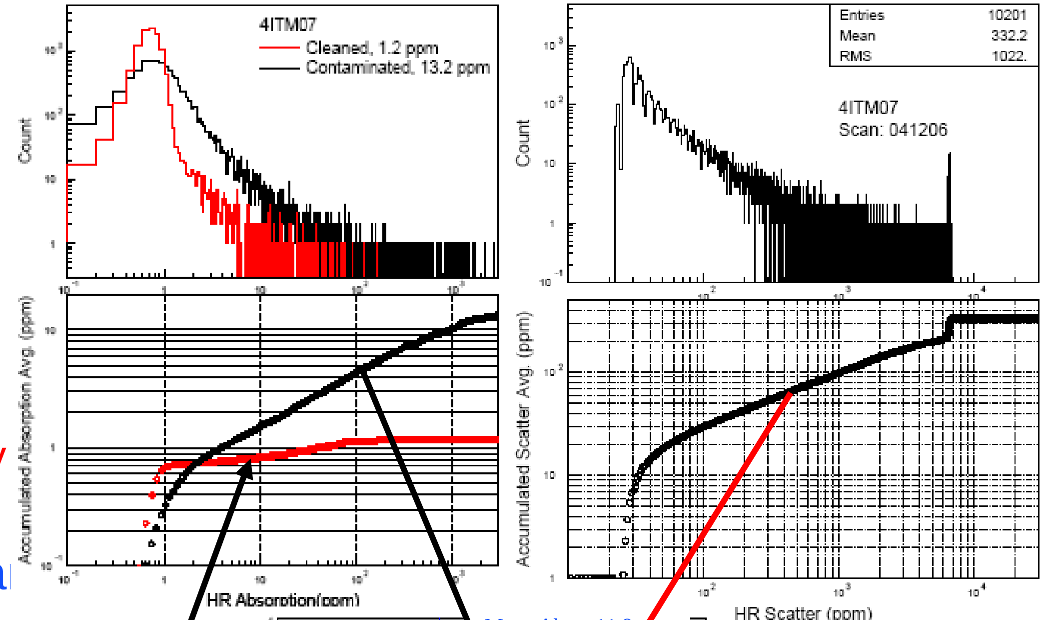
Contamination & thermal lensing

- ~7 years of installed Core optics
  - » No evidence of *accumulating* contamination (scattering or absorbing)
    - – Routine full lock only ~5 yrs. High power only 1-2 yrs.
    - – Some optics >6 yrs hanging have no evidence of HR absorption >1ppm (design)
    - – Net scatter loss seems independent of TM installation epoch (though high !)
  - » *Residual* absorption has been found consistent with materials/Fab. expected.
    - – As anticipated by simulations, this level essentially only affects SB fields
    - – Bulk silica absorption not controlled sufficiently for "point" thermal design.
    - – "TCS" system required for compensating residual variations.

- This *typical* experience: extrapolates well to Adv. LIGO !
  - » Outstanding discrepancy: installed TM scatter loss far too high
    - – Assumed either treatable "dust" issue; or adjustment of coating process
- However also **contamination accidents**
    - – High power operation revealed >10x residual coating absorption
    - – Unique to pair of ITMs: no evidence in other Hanford optics. ***When ??***

Contamination in LIGO I TMs

- Goal: corroborate in situ performance with bench tests
  - » Many LIGO COC optics studied
    - – Comparisons establish “typical” from anomalous
  - » Absolute calibration to various reference mirrors.
    - ➢ Components of “loss test” cavity



Example: What is anomalous conta on H1 ITMs?

- ➢ Absorption is lumpy but not point like
- ➢ Scatter also anomalous and correlates well spatially with absorption
- ➢ <u>Easily removed by surface cleansing</u>
- ➢ Fine absorbing dust, sucked in during vent?