

LIGO *Core* Optics:

a decade of development and experience

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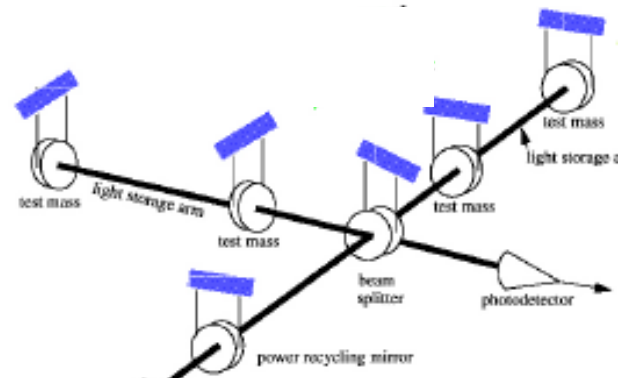
LIGO Laboratory, Caltech

With acknowledgement of entire LIGO team for its optical
development

LIGO “Core” Optics

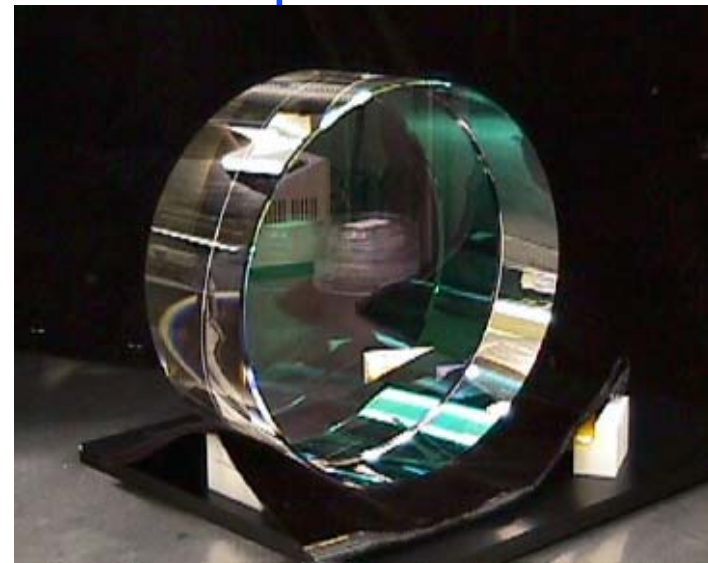
- 6 (4 test masses; splitter; recycling mirror) large ϕ optics which form high power cavities.

- » 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 \Rightarrow 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: $r_{ifo} >/< 0$ (point design recycling)

Optical Loss Expectations

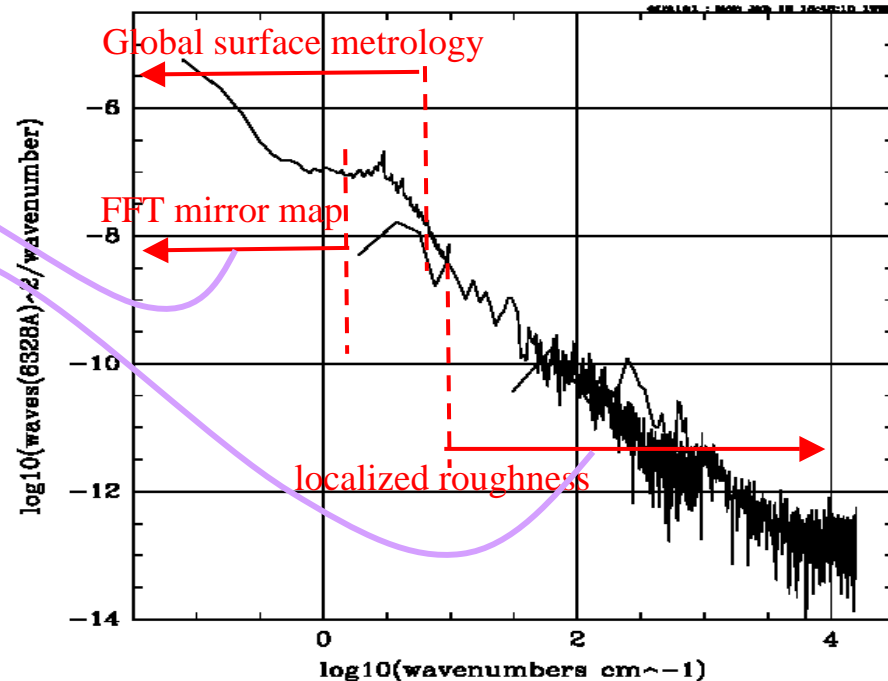
- Goal: $G_{RC}^{CR} \geq 30$ based on older polish/coating information
- Pathfinder development & fabrication proved much better:
 - » Micro roughness $\sigma_{rms} < 0.28 \text{ nm} \Rightarrow$ prompt loss $\sim (4 \pi \sigma_{rms} / \lambda)^2 < 10 \text{ ppm}$
 - » Super polished substrate 2 - 3x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

➤ Simulation (FFT) with Fab. Data:

- Figure= modal distortion
- Roughness= loss
- Low absorption= cold “start up”
- Witness sample reflectivity

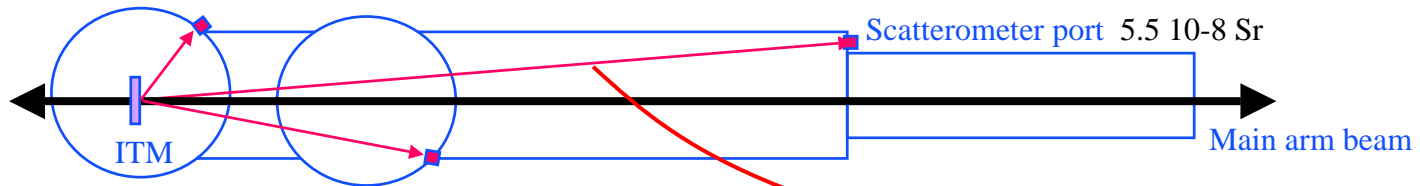
Simulated G (at least: CR field not affected by degenerate recycling) far exceeds goals

- **Consistent with Advanced ligo requirements**

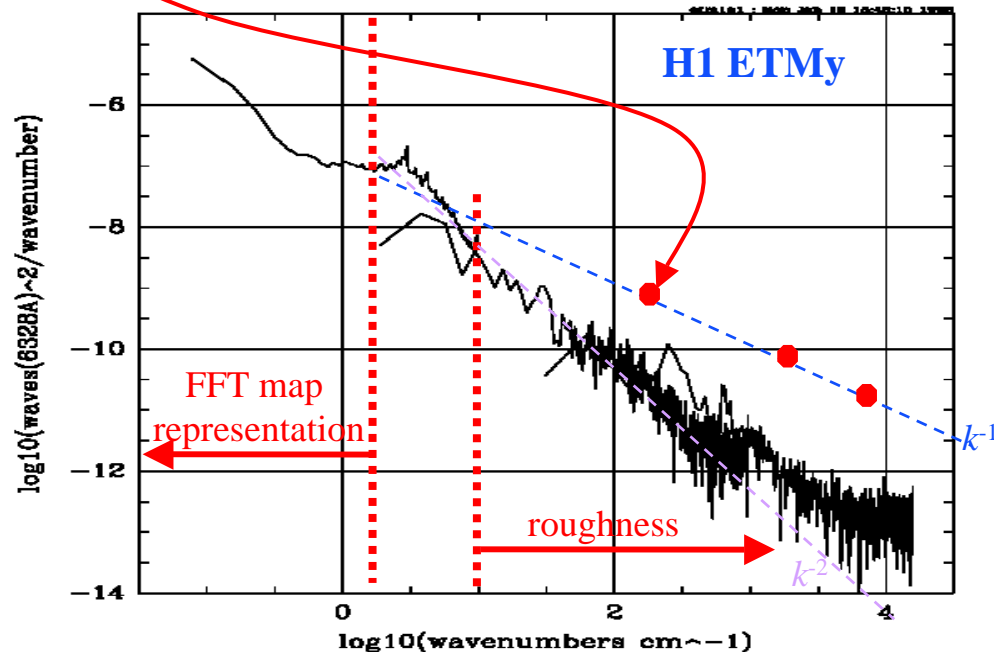


Scatterometer studies

- 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

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

Replaced ITM

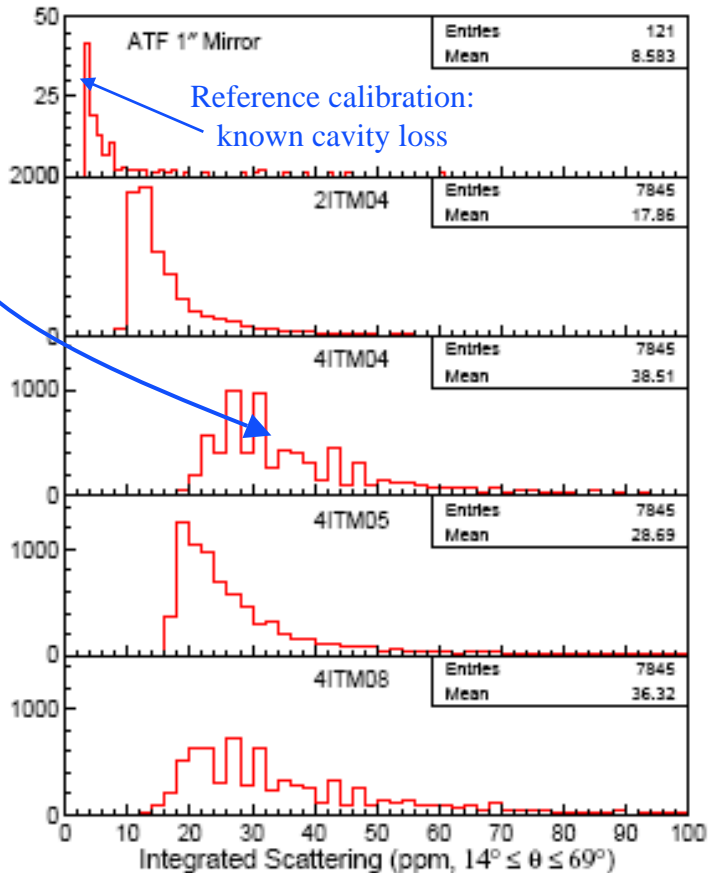
CAVITY	V	T_{ITM}	$T_{WITNESS}$	Scatter
2k X	.0222	.0277	.0283	0.85
2k Y	.0211	.0272	.0281	7
4k X	.0241	.0279	.0275	7.5
4k Y	.0214	.0263	.028	8.8

- » 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??

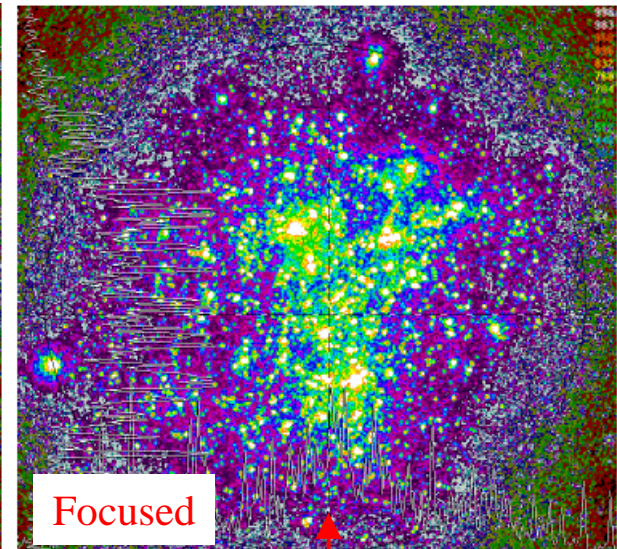
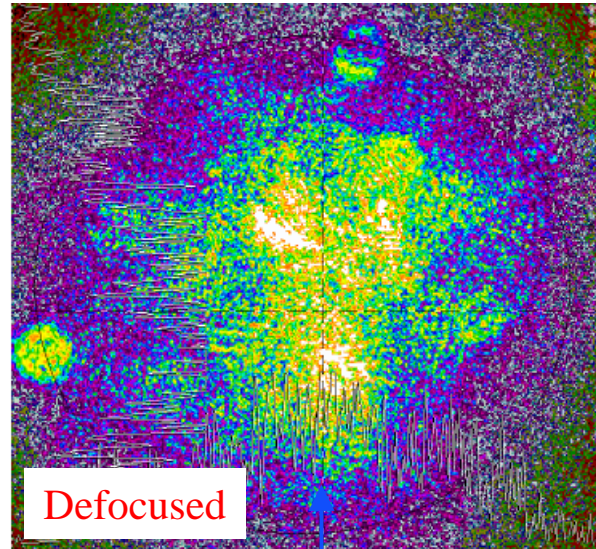


Resonant arm, Gaussian illuminated ETM

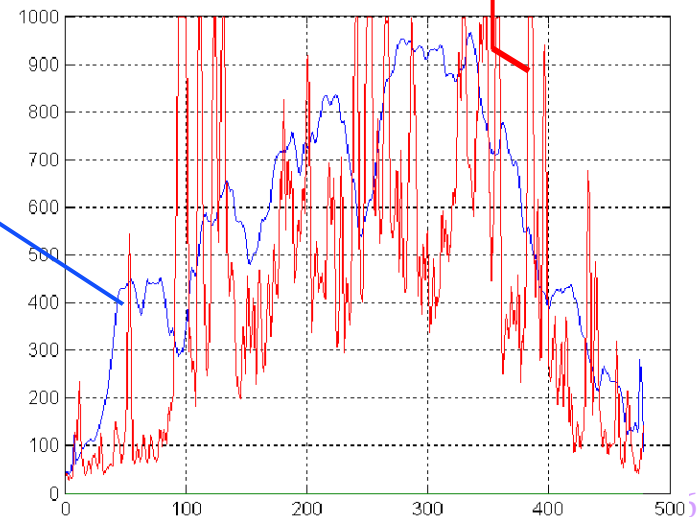
Analysis of the “Globular Cluster”

- 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

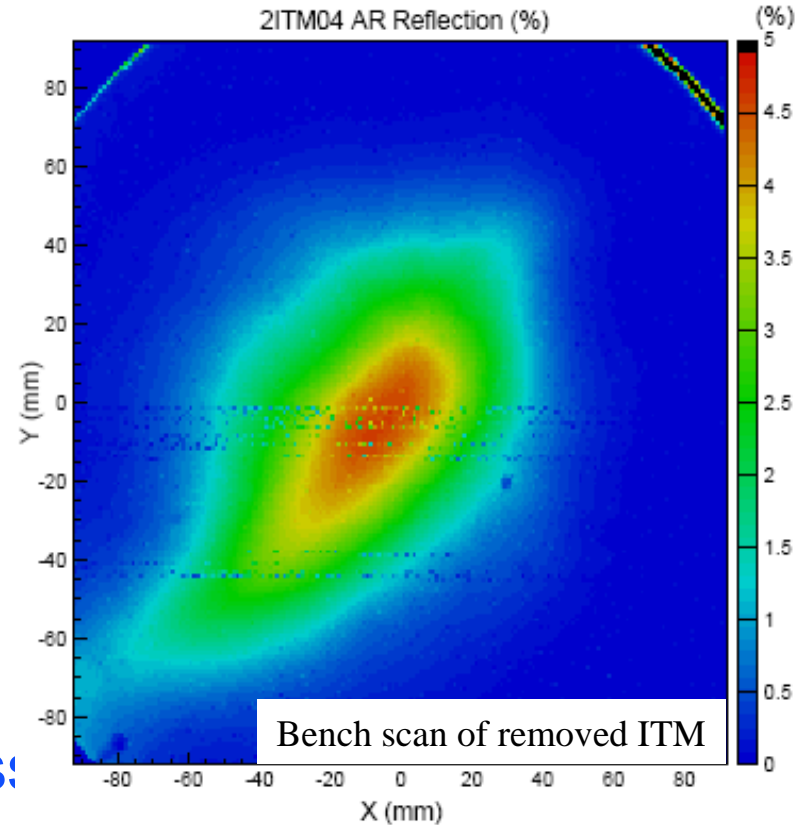
- For several years Hanford 2k performed poorly

- » 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).



- ~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 contamination on H1 ITMs?

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

