# Studies of Thermal Loading in Pre-Modecleaners for Advanced LIGO

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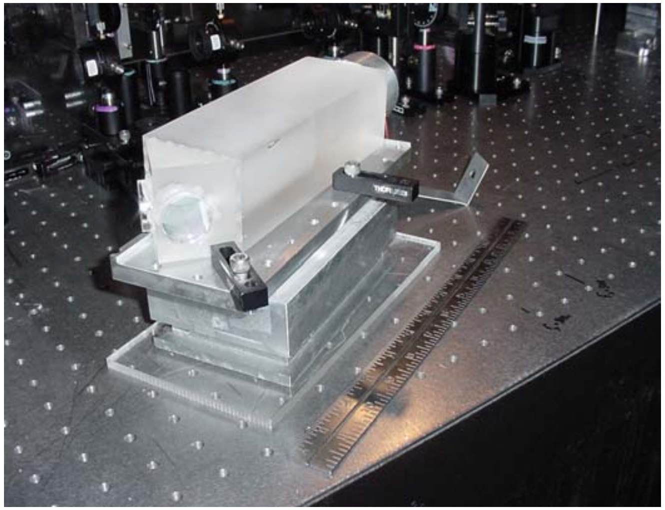
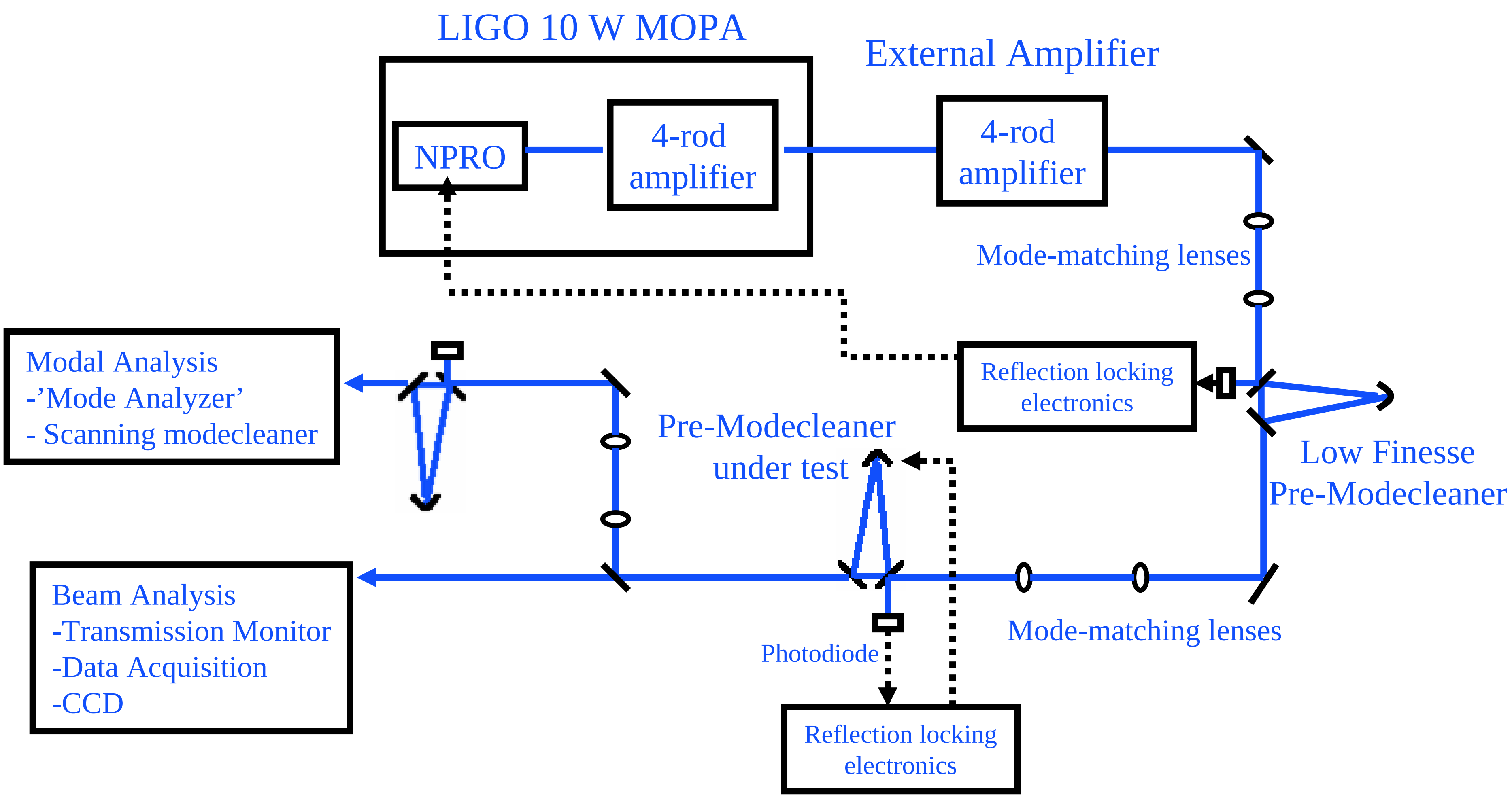
# Outline

- Thermal Loading Experiment
  - » Ring cavity known as pre-modecleaner (PMC)
    - – Same geometry as cavity used in the PSL
  - » Goal: Achieve resonant thermal load akin to Advanced LIGO
    - – Use calibrated absorption loss
    - – Reach absorption comparable to Advanced LIGO
      - ~12 mW per suspended MC optic for 0.5 ppm coating absorption
    - – Compare results to models
- Results
  - » Onset of thermal loading
  - » Thermal limits
- For the future
  - » Further tests
  - » Suggestions

A Pre-Modecleaner



# Experimental Setup

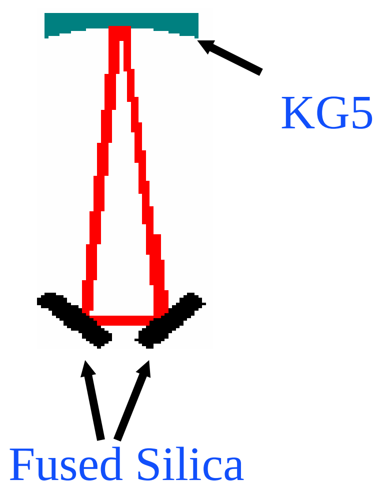


LIGO

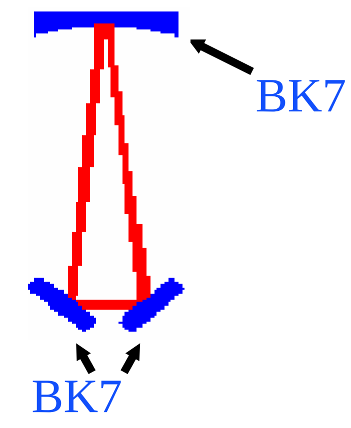
# Pre-Modecleaner Properties

- Dominant thermal load in coatings
  - » Low-loss coatings coated by Research Electro-Optics
  - » Absorption loss measured by PCI
    - – Flat I/O optics: 1.4 ppm
    - – Curved optic: 0.4 ppm
- 'Lossy' pre-modecleaner
  - » Low-loss fused silica input/output optics
  - » Rear optic: low-loss coating on absorptive substrate
    - – IR absorbing glass: KG5
    - – KG5 optic coating transmission: 81 ppm
- 'Low-loss' pre-modecleaner
  - » REO coatings on BK7 substrates
- Resonances of different polarizations do not overlap
    - – Low Finesse (p-pol) ~ 330
    - – High Finesse (s-pol) ~ 5000

'Lossy' Pre-modecleaner



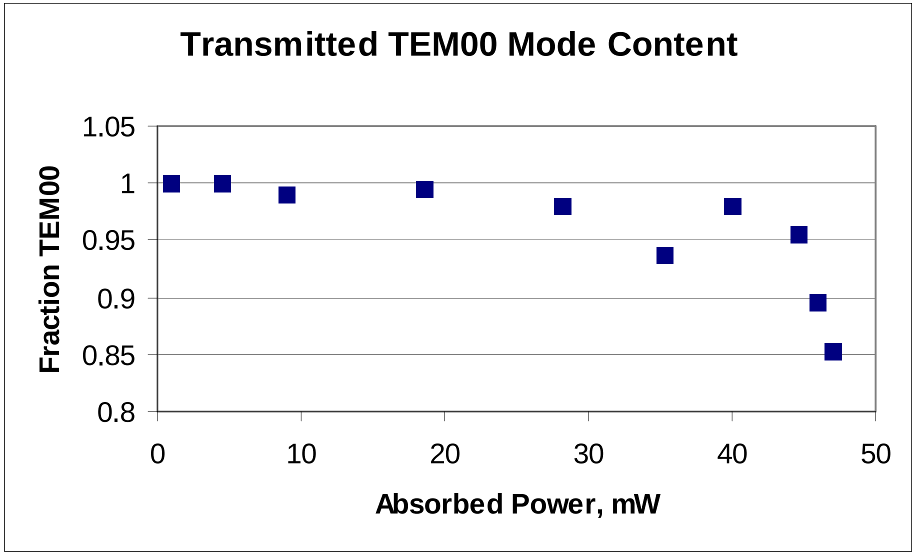

'Low-loss' Pre-modecleaner



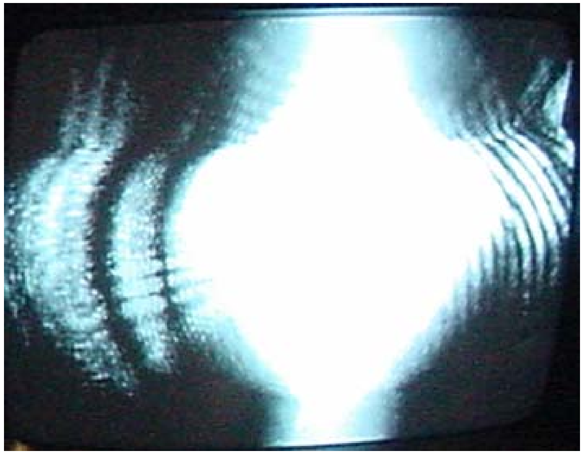
LIGO

# 'Lossy' Pre-Modecleaner – Low Finesse

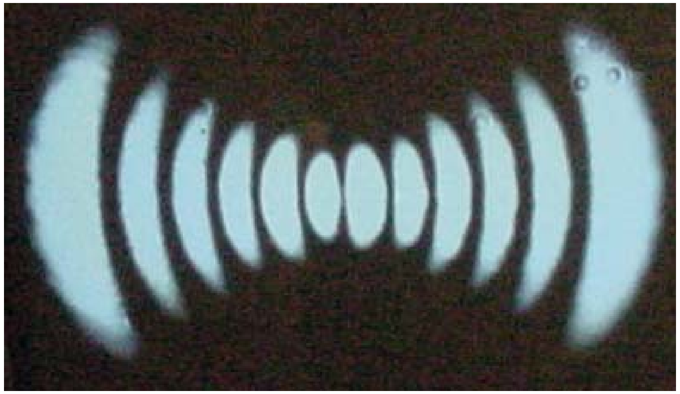
- Increase input power in steps
  - » Analyze transmitted $TEM_{00}$ content
- Higher order mode overlap with $TEM_{00}$
  - » Occasional overlap seen as power is increased
  - » Roll-off in $TEM_{00}$ content at high absorbed power




Transmitted CCD Image – 'Lossy' PMC

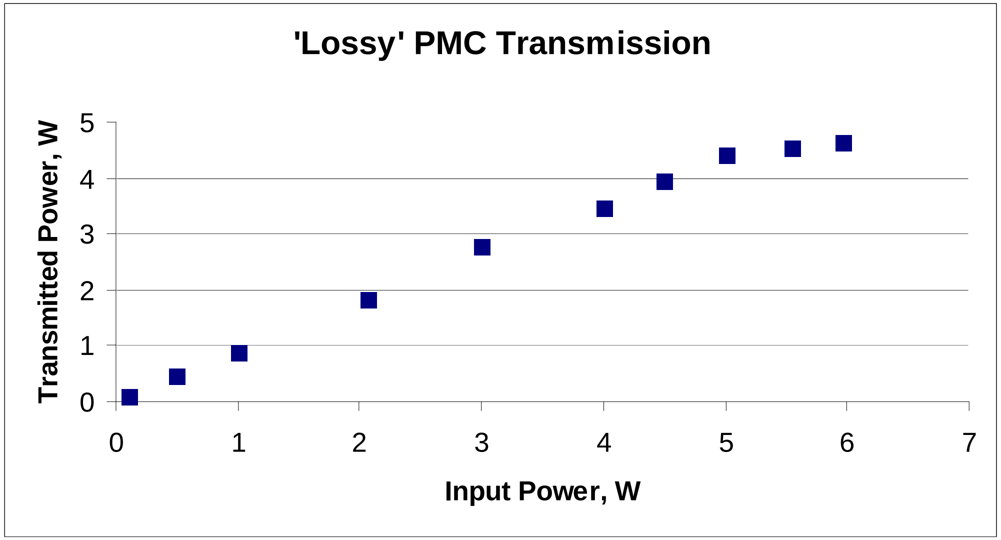


CCD Image – Mode Analyzer PMC



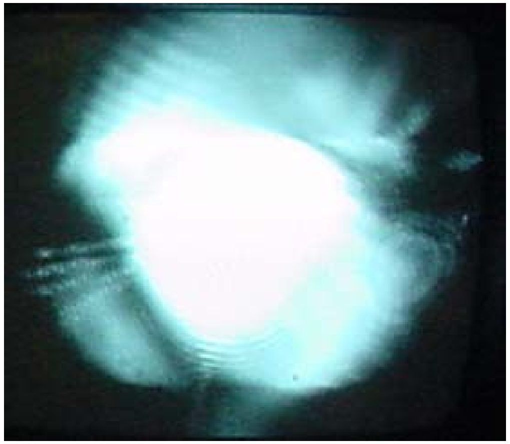
# 'Lossy' PMC Thermal Limit

- Thermal Limit
  - Transmission linear up to 5 W input power ($P_{absorbed}$ = 40 mW)
  - For $P_{absorbed}$ > 40 mW, higher order modal content degrades transmitted beam quality
  - For $P_{absorbed}$ > 47 mW, constant locked transmitted power not achieved



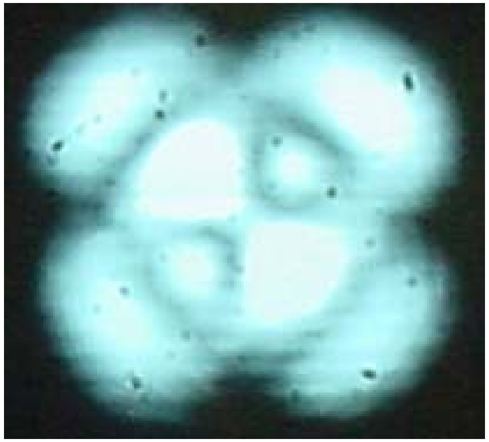

'Lossy' PMC Images

Transmitted Beam

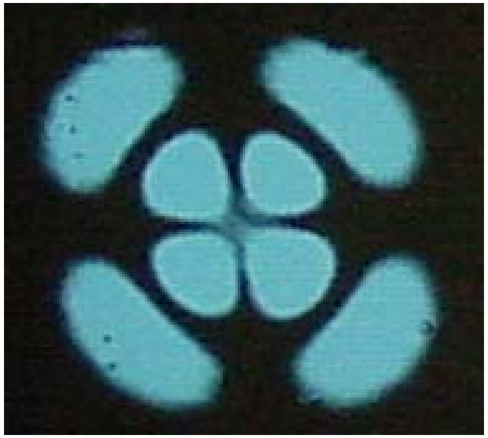


Input Power = 6 W, $P_{absorbed}$ = 47 mW

Reflected Beam

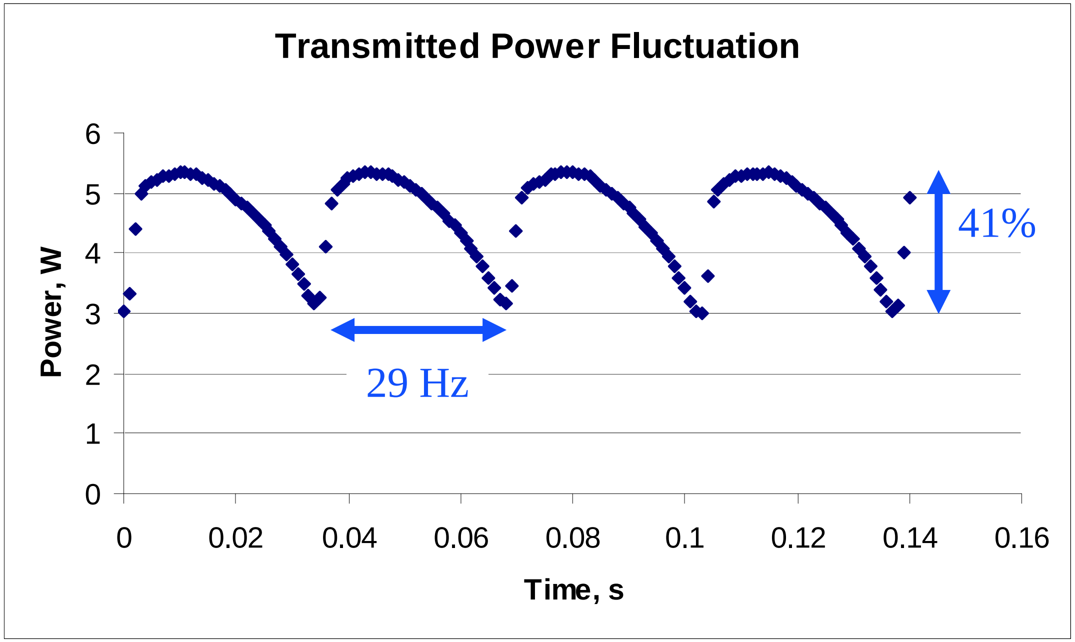


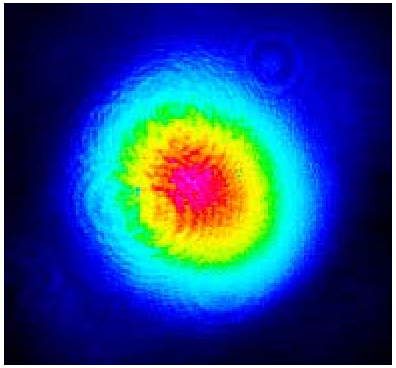
Mode Analyzer Transmission



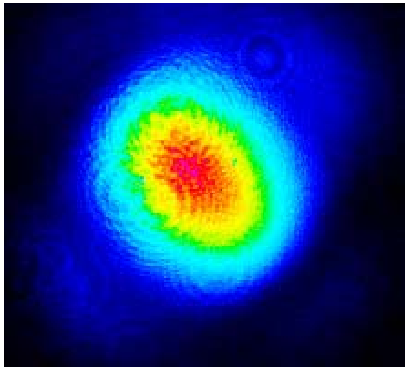
# Thermally Induced Power Fluctuation

- Power fluctuation from thermal effects
  - » Lossy PMC: Thermal cycling induces periodic fluctuation of transmitted power
- Transmitted mode images
  - 1: near maximum power
  - 2: during power decline
  - 3: near minimum power



1



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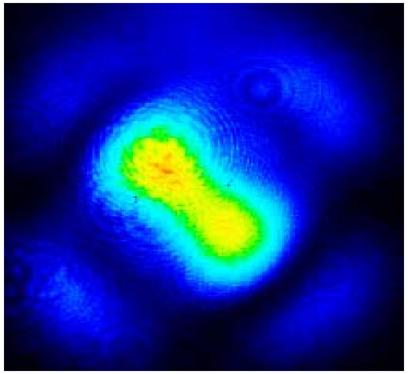

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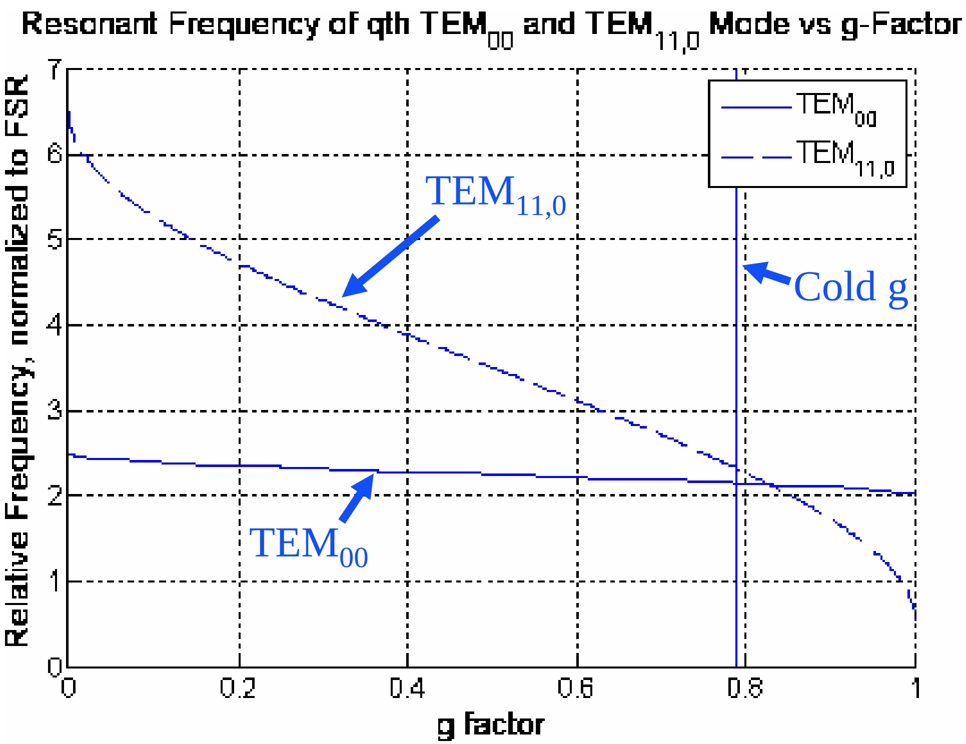
LIGO

# Modal Analysis

- Higher order mode overlap with $TEM_{00}$
  - » Change in cavity g-factor: $g = 1 - L/R$
  - » Change in Radius of Curvature (ROC) of KG5 optic
- New g factor gives thermally distorted radius of curvature, $R_{hot}$
  - » Cold cavity g factor = 0.79
    - – $R_{cold}$ = 1 m
  - » Example: $TEM_{00}/TEM_{11,0}$ overlap
    - – Hot cavity g factor = 0.83
    - – $R_{hot}$ = 1.2 m
- Calculate absorbed power from $R_{hot}$, compare with expected absorption
  - » $P_{absorbed} = (4\pi\kappa\delta s)/\alpha$

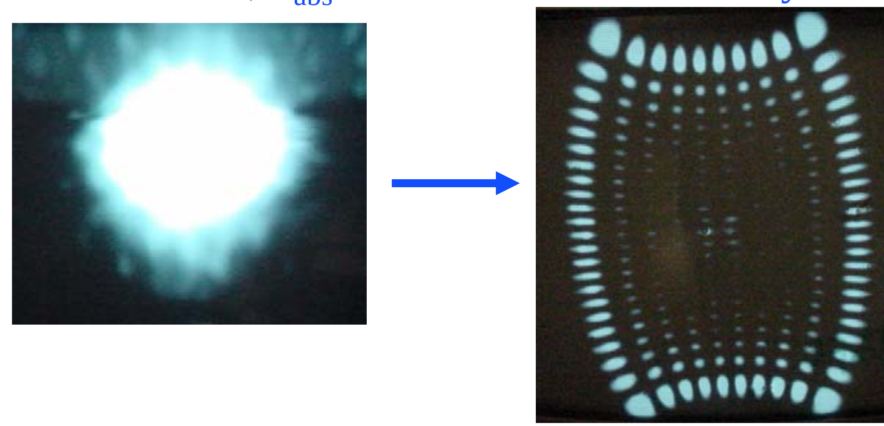



| Input Power | Calculated Absorbed Power | Expected Absorbed Power | Observed Mode |
|---|---|---|---|
| 1 W | 13 mW | 9 mW | $LG_{23}$ |
| 4 W | 23 mW | 30 mW | $TEM_{11,0}$ |
| > 4.5 W | 39 mW | 40 mW | $LG_{12}$ |

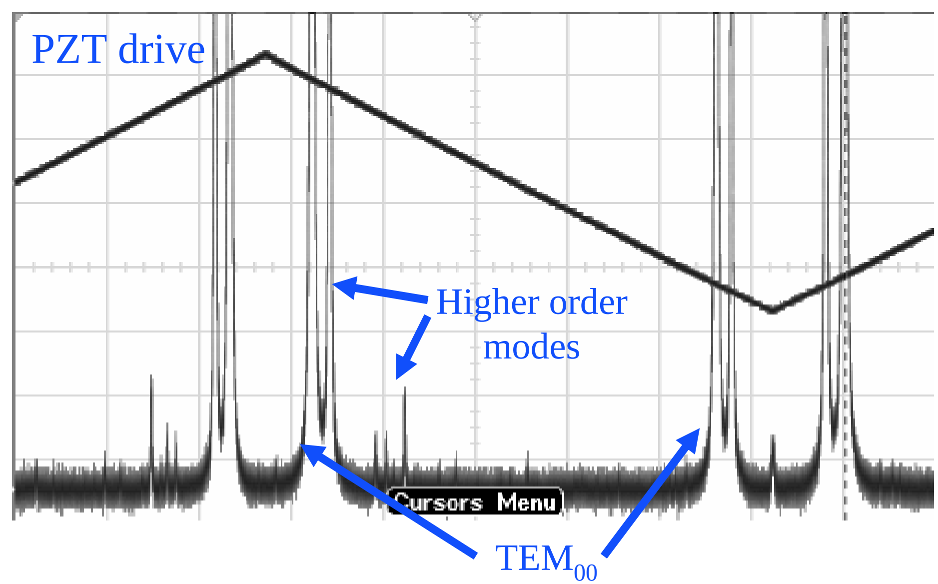
# ‘Lossy’ Pre-Modecleaner – High Finesse

- Strong higher order mode coupling
  - » First observation at 4.25 mW absorbed power
    - – Several $TEM_{mn}$, large m+n, modes
    - – 96 % $TEM_{00}$ output
- Degradation of $TEM_{00}$ output
  - » Increased absorbed power
    - – Multiple higher order mode coupling
    - – Sometimes one dominant higher order mode
  - » Lowest $TEM_{00}$ transmission 57% at 12 mW absorbed power

Transmitted Beam, $P_{abs}$ ~ 4 mW | Mode Analyzer



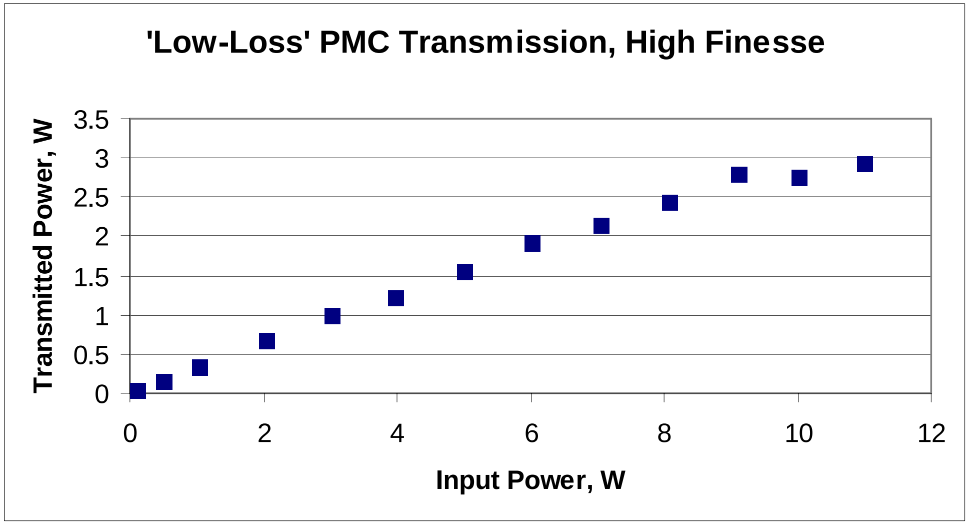
Mode Analyzer, $P_{abs}$ ~ 10 mW

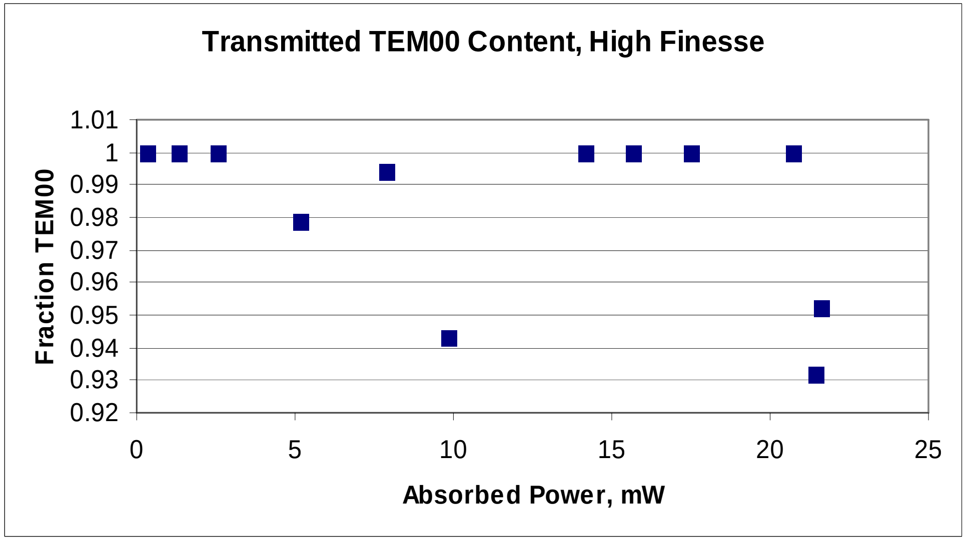


LIGO

# 'Low-loss' Pre-Modecleaner

- REO coatings on BK7 substrates
- High finesse
  - » Higher order modes at a few absorbed powers, starting at $P_{abs}$ = 5.1 mW
  - » Rollover in transmission > 20 mW absorbed power
- Low Finesse
  - » First higher order mode coupling noted near max available input power, $P_{abs}$ = 5.1 mW



# Other Issues

- Reduced transmission in high finesse for both pre-modecleaners
  - » 30% coupling, expect closer to 80%
  - » Scatter loss from curved optic
  - » Response to thermal load agrees with expected absorption
- Melody
  - » Mode-based interferometer thermal modeling tool
  - » Limited agreement with data
    - – Thermal loading of ‘Lossy’ PMC in low finesse
    - – Differing behavior for thermal loading in high finesse
      - Melody shows sharp coupling decline without higher order mode coupling

# Summary

- Transmission degradation from higher order mode coupling
  - » Stronger coupling in high finesse case
  - » Large thermal load may induce power fluctuations

- Recommendations based on observations
  - » Coating absorption <= 1ppm
  - » Higher finesse -> lower absorption
    - – From experiment, < 4 mW
    - – Scale results to other substrate materials
  - » Aperture to suppress large order modes
    - – Suspended modecleaner
  - » Consider alternative geometry
    - – 4-bounce pre-modecleaner?
      - Advantage: reduce mode overlap possibility
      - Disadvantage: not polarization sensitive

- For the future …
  - » Test pre-modecleaners with sapphire and undoped YAG optical substrates
  - » Design an all-reflective modecleaner using gratings
    - – Expand substrate possibilities (e.g. silicon)