Deformable Optics
&
Wavefront Sensing

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Galileo Project

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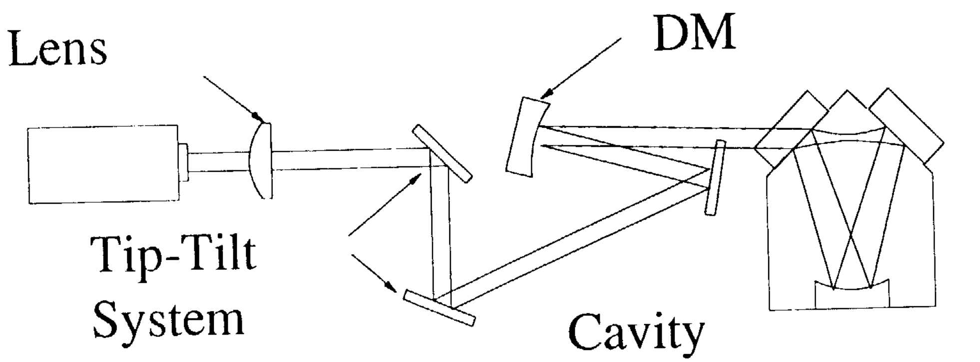
LIGO-G980049-23-M

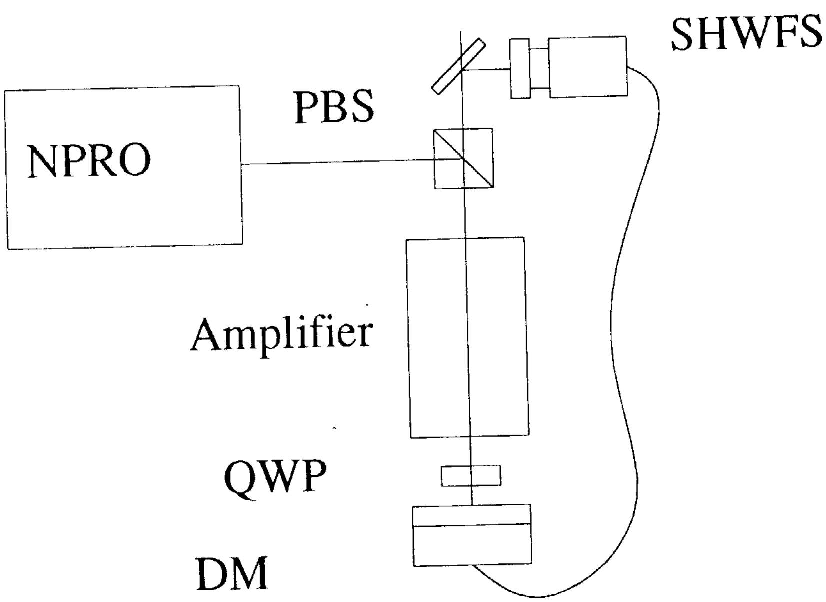
Outline

- Introduction and Motivation
- Deformable Mirrors
- Active Mode Matching
- Conclusions and Future Work

Applications of Deformable Optics



Active Mode Matching



Advanced Laser Amplifier

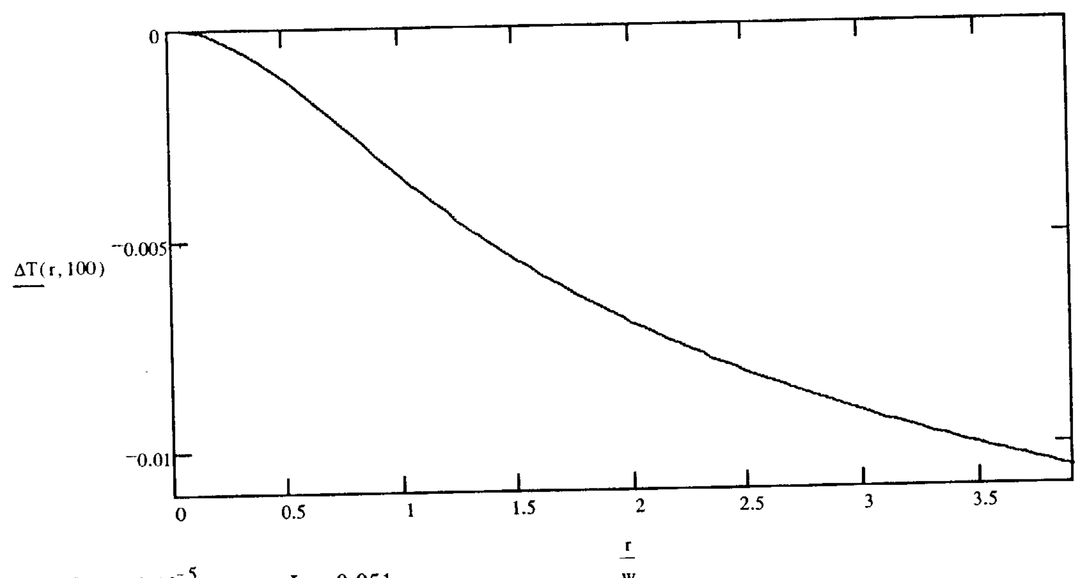
Thermal Lensing

- Absorption causes heating
- Temperature change causes:
  - Index of refraction shift
  - Expansion
  - Strain induced index shift

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{q'''}{k_{th}}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

q'''=heat sources (W/m^3)

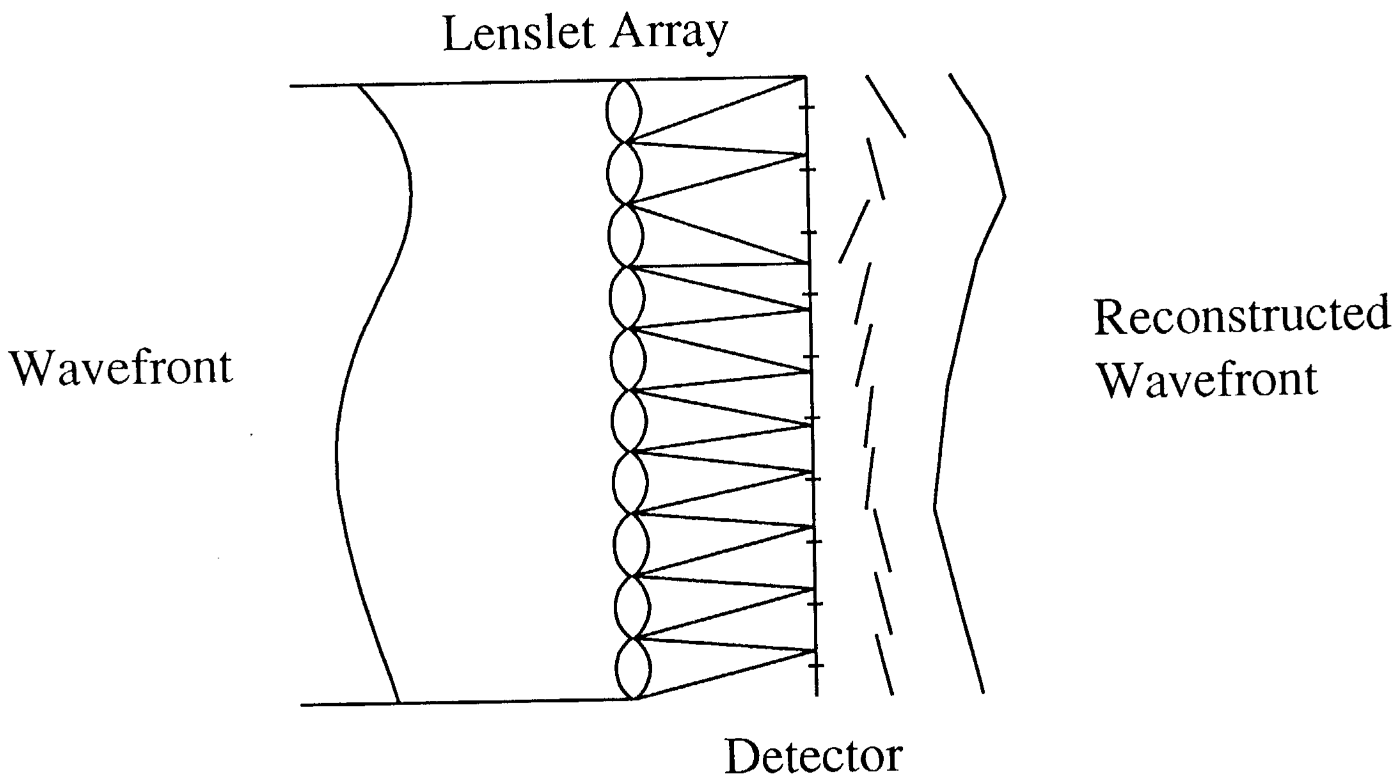
$$T(r)=T_0+\frac{P_{abs}}{4\pi k_{th}}\sum_{k=1}^{\infty}\left(2\frac{r^2}{w^2}\right)^k\frac{(-1)^k}{kk!}$$



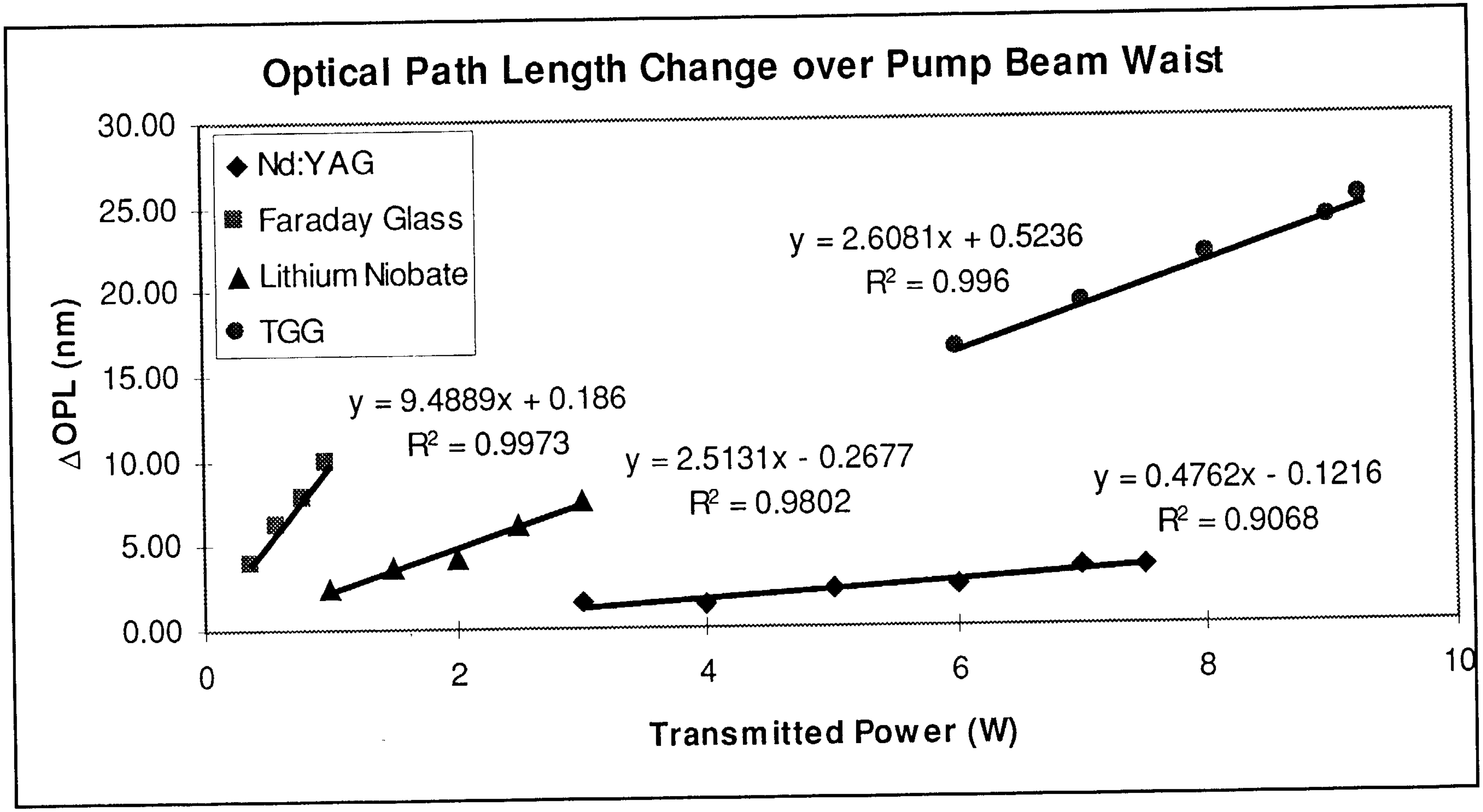
$\beta := 3.8\cdot 10^{-5}$ $L := 0.051$

Shack-Hartmann Wavefront Sensor

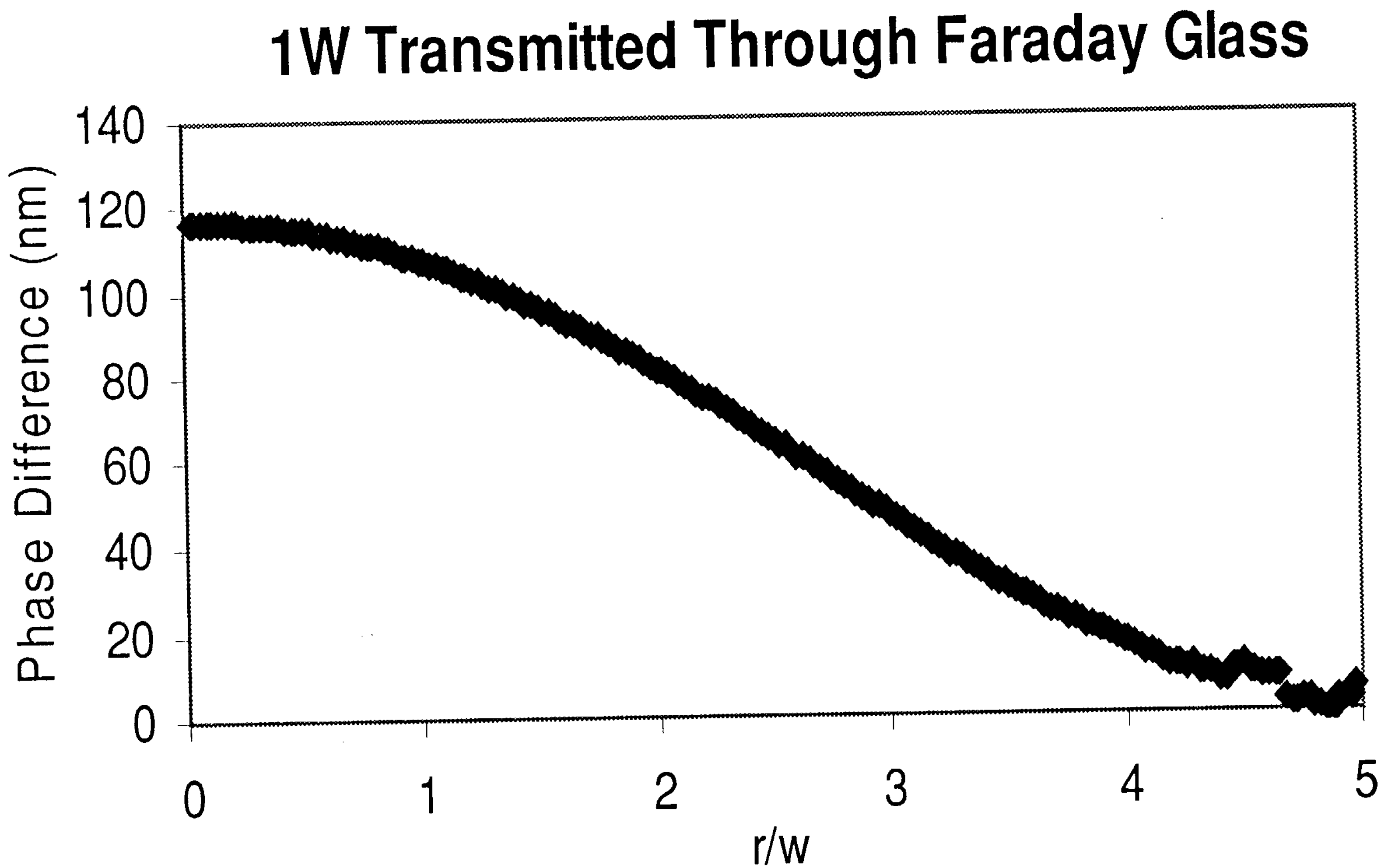
- Phase slope is detected by determining the position of an array of spots
- Wavefront is reconstructed by doing a form of integration



Measured Thermal Lensing

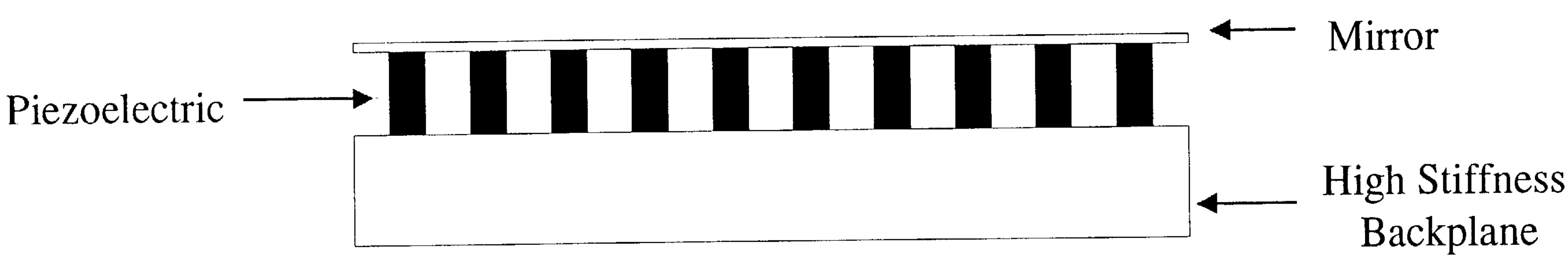


Measured Thermal Lens Shape



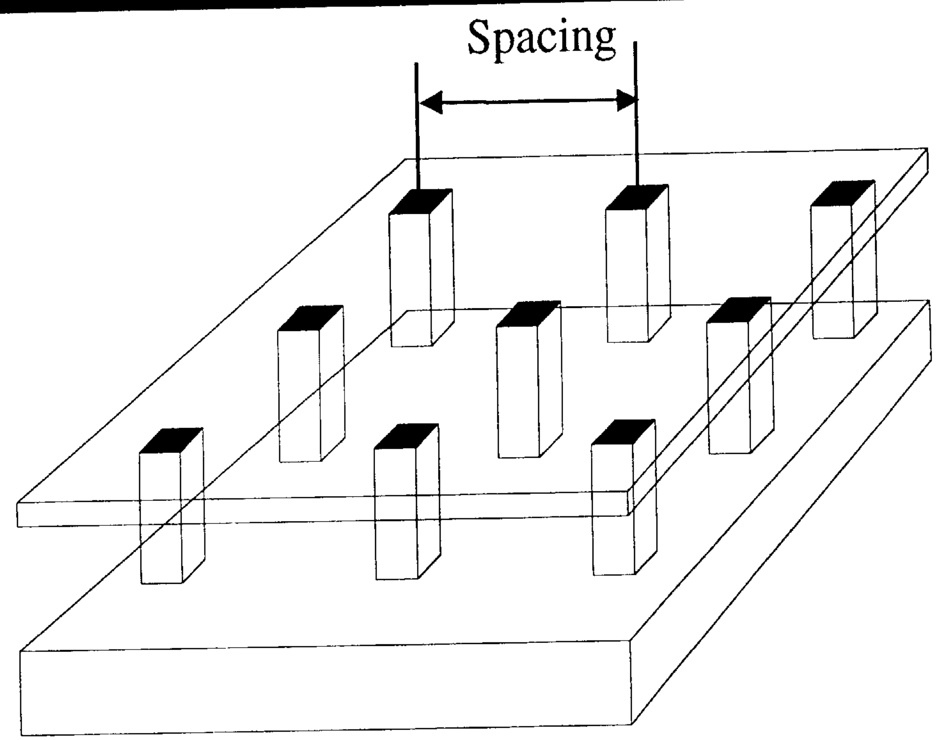
Brief History of Adaptive Optics

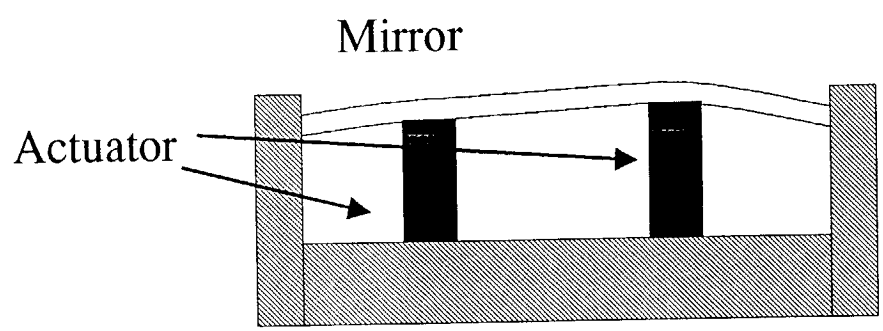
- 212BC - Archimedes attempt to set fire to the Roman fleet at Syracuse using “burning mirrors”
- 1953 - Horace Babcock and James G. Baker discussed real adaptive optics systems.
- 1958 - Babcock suggested an electrostatic membrane mirror.
- 1973 - Real Time Atmospheric Compensation (RTAC) by Itek used a 21 element piezoelectric mirror and a shearing interferometer.



Deformable Mirror Specifications

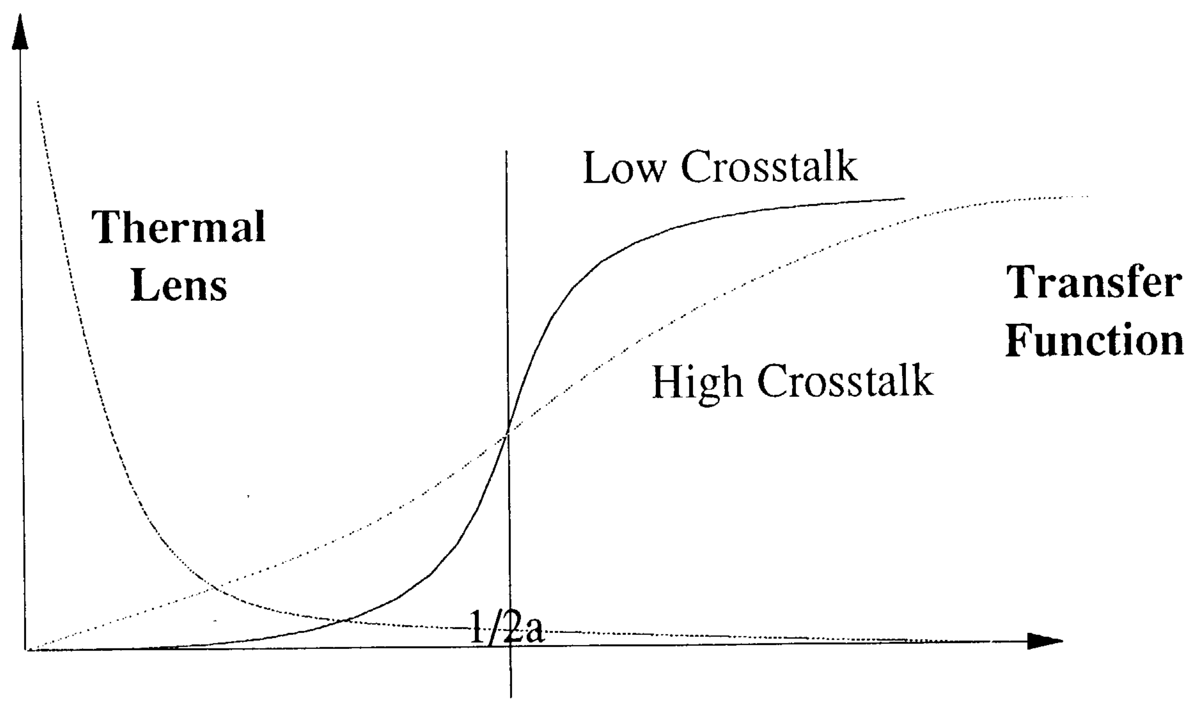
- Actuator spacing
- Actuator geometry
- Actuator cross-talk
- Mirror resonance
- Mirror reflectivity and surface quality





Adaptive Optics Systems

- Adaptive optics systems are high-pass spatial frequency filters.



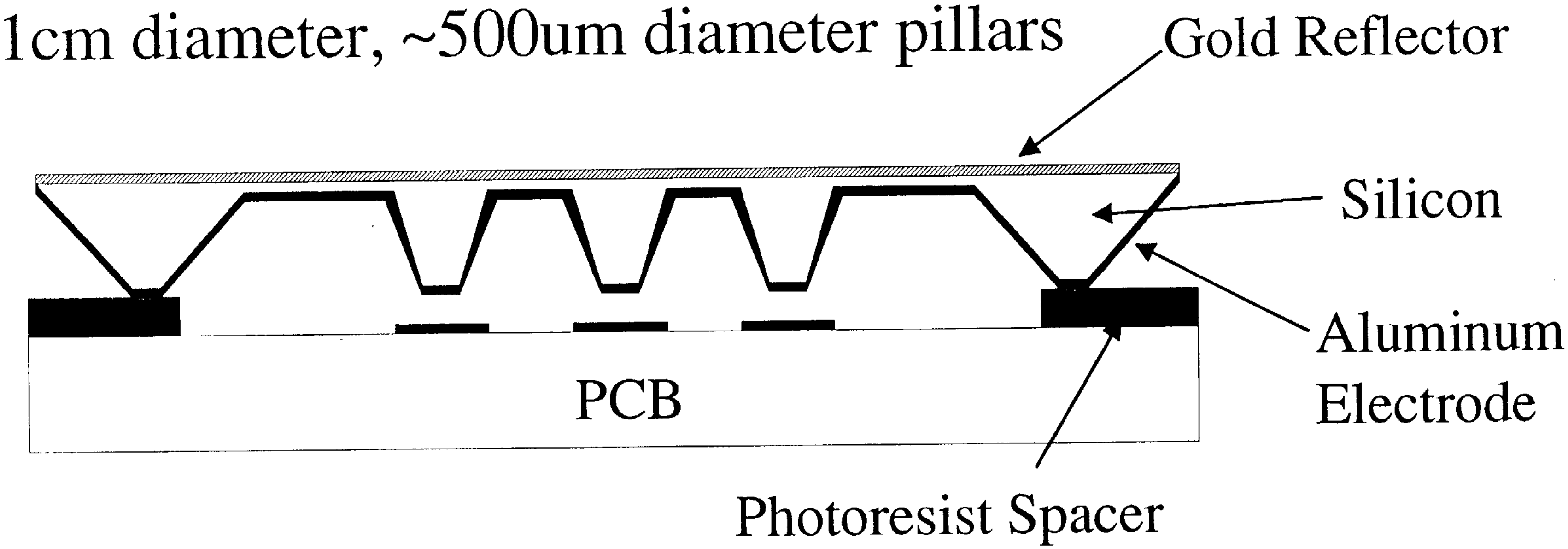
Robert K. Tyson "Theoretical studies of system performance and adaptive optics design parameters". SPIE vol 1271

Problems with Commercial DMs for LIGO

- PZT or PMN actuated mirrors
  - High cost (~$1000 per actuator)
  - Low reflectivity (aluminum coating)
- Si_3N_4 Deformable Mirror
  - $5W/cm^2$ maximum intensity
  - 200Hz Resonance
- Surface Micromachined Silicon DM
  - Poor surface quality
  - Low reflectivity (uncoated)

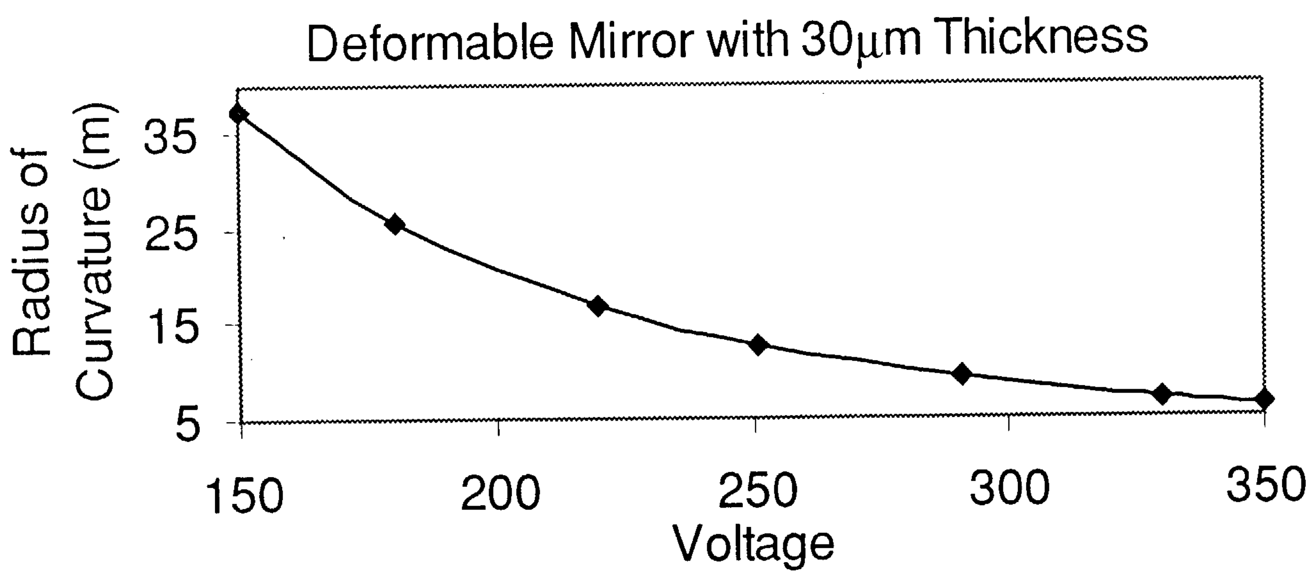
Stanford Silicon Deformable Mirror

- Advantages of Silicon
  - Can be highly polished
  - Good mechanical properties
  - Micromachining techniques
  - High thermal conductivity
- 1cm diameter, ~500um diameter pillars



Silicon Deformable Mirror Properties

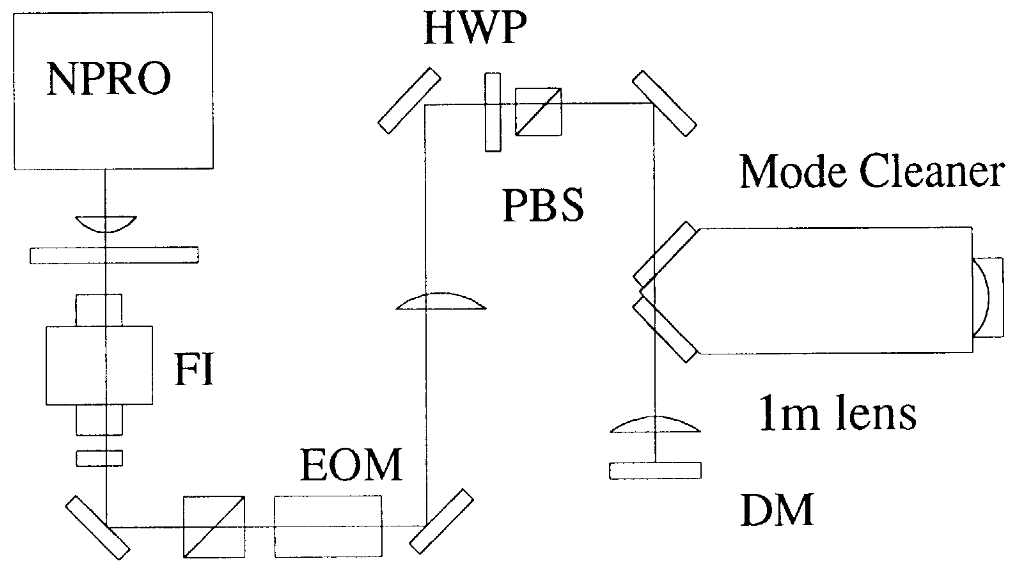
- 100nm of gold on 20 microns of silicon held 100kW/cm^2
- First resonance at 950Hz and 2.7kHz for 10 micron and 30 micron thickness respectively
- Adjacent channel crosstalk of about 56% for 1.8cm diameter mirror and 4mm actuator spacing

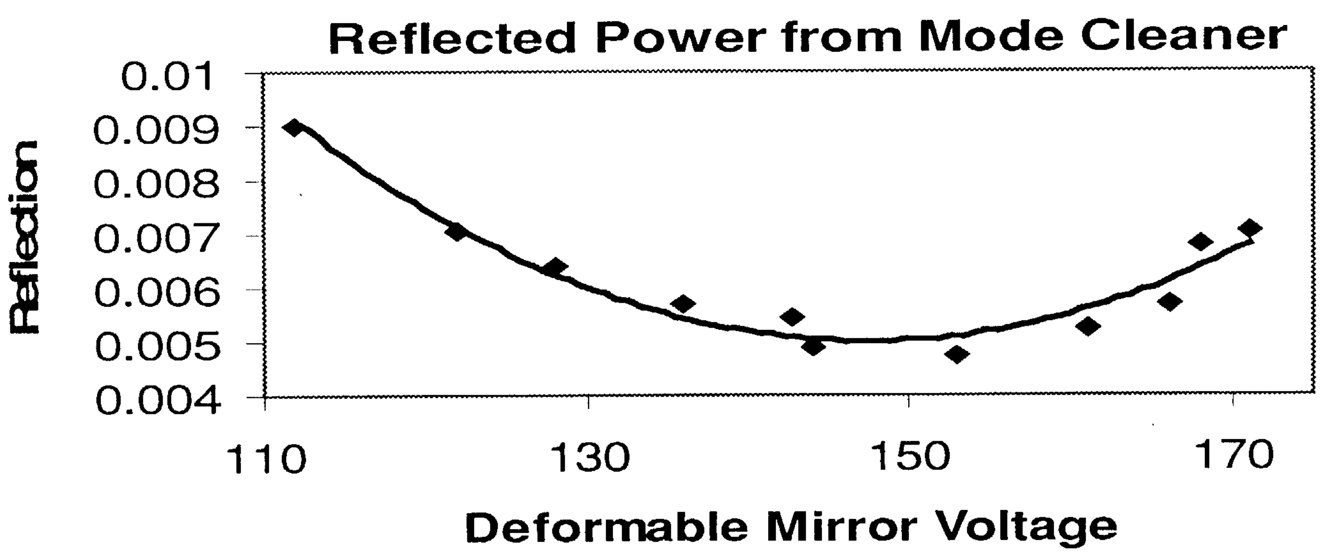


Active Mode Matching

Benno Willke and Justin Mansell

- 22cm to lens
- 5cm to DM
- 0.0048 relflected at minimum





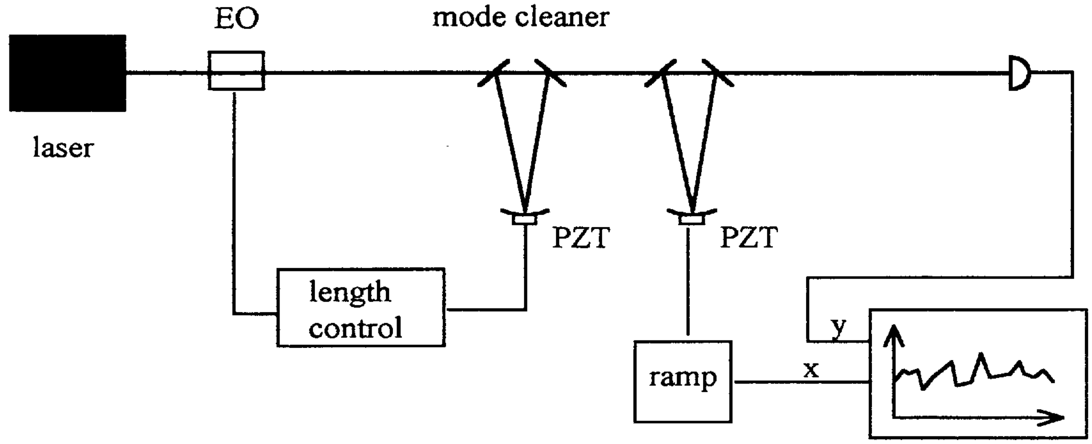
Conclusions

- We have developed a new silicon deformable mirror architecture to meet the needs of LIGO.
- We have demonstrated active mode matching with a silicon deformable mirror.

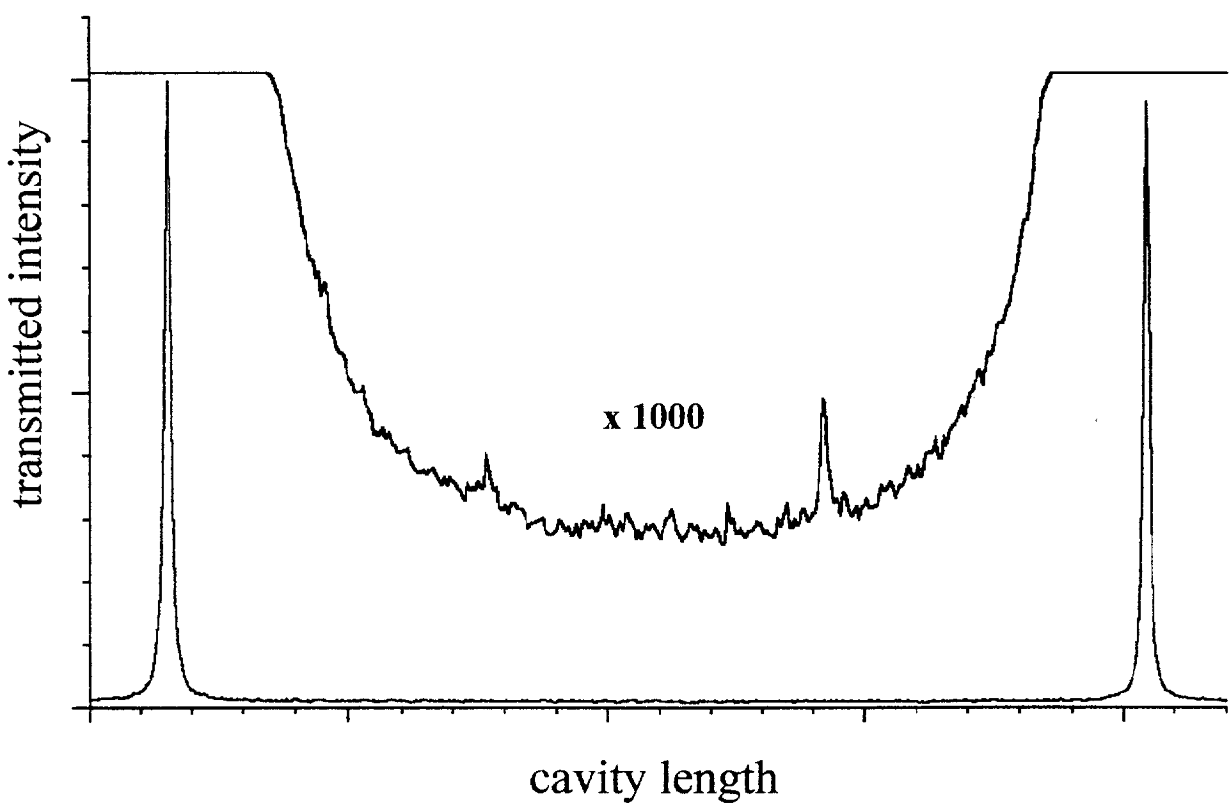
summary

- intensity noise at 25MHz is 2 times higher than expected
- pre mode cleaner was implemented
  - intensity noise filtering above 2MHz
  - the expected amount of spatial filtering was measured
  - phase noise introduced by pre mode cleaner "length noise" has to be reduced
- we reduced the relative intensity noise in the gravitational wave band to $2 * 10^{-7} / \sqrt{Hz}$
  - cross coupling between NPRO was measured

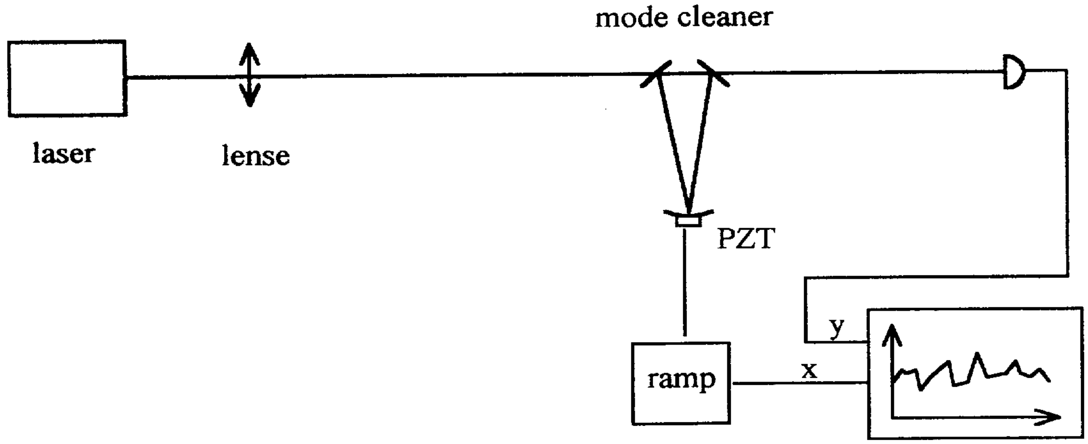
mode filtering



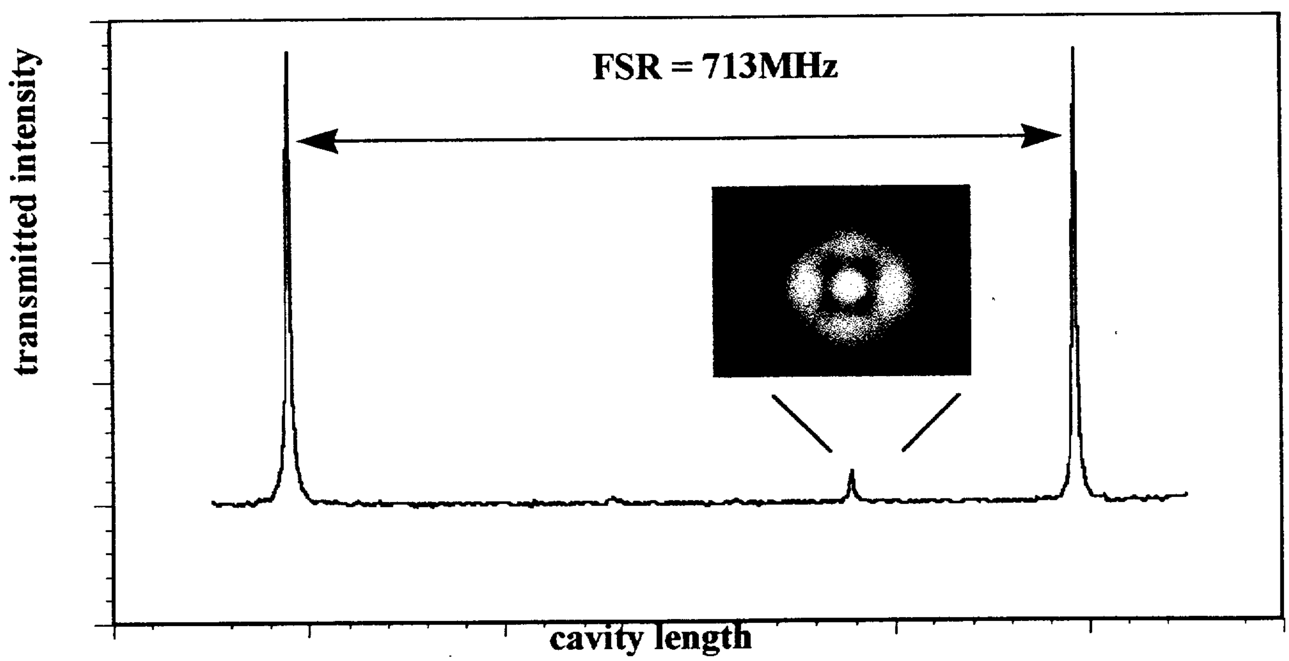
LIGO 10W laser behind pre-mode cleaner

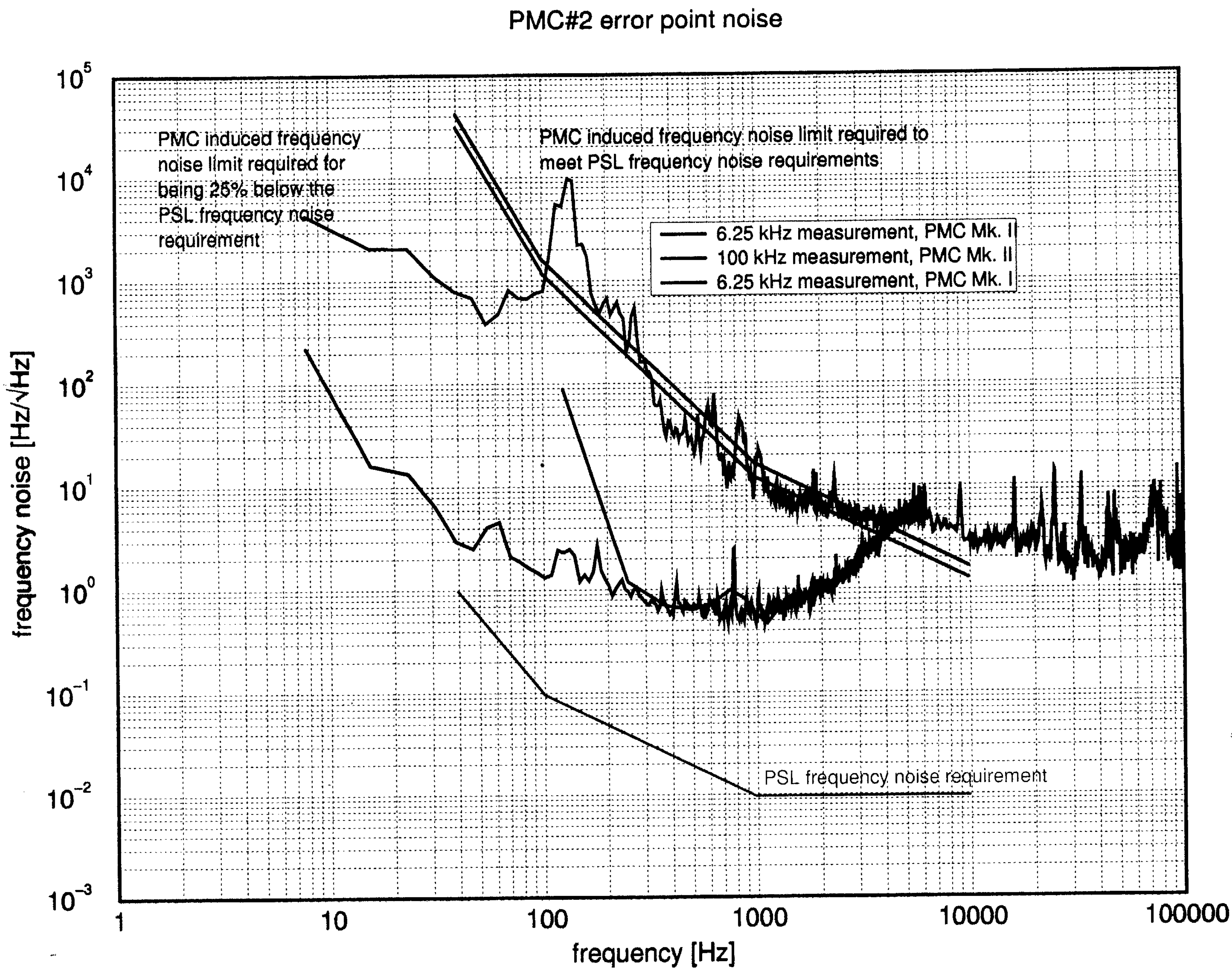


beam profile measurement



example: LIGO 10W laser

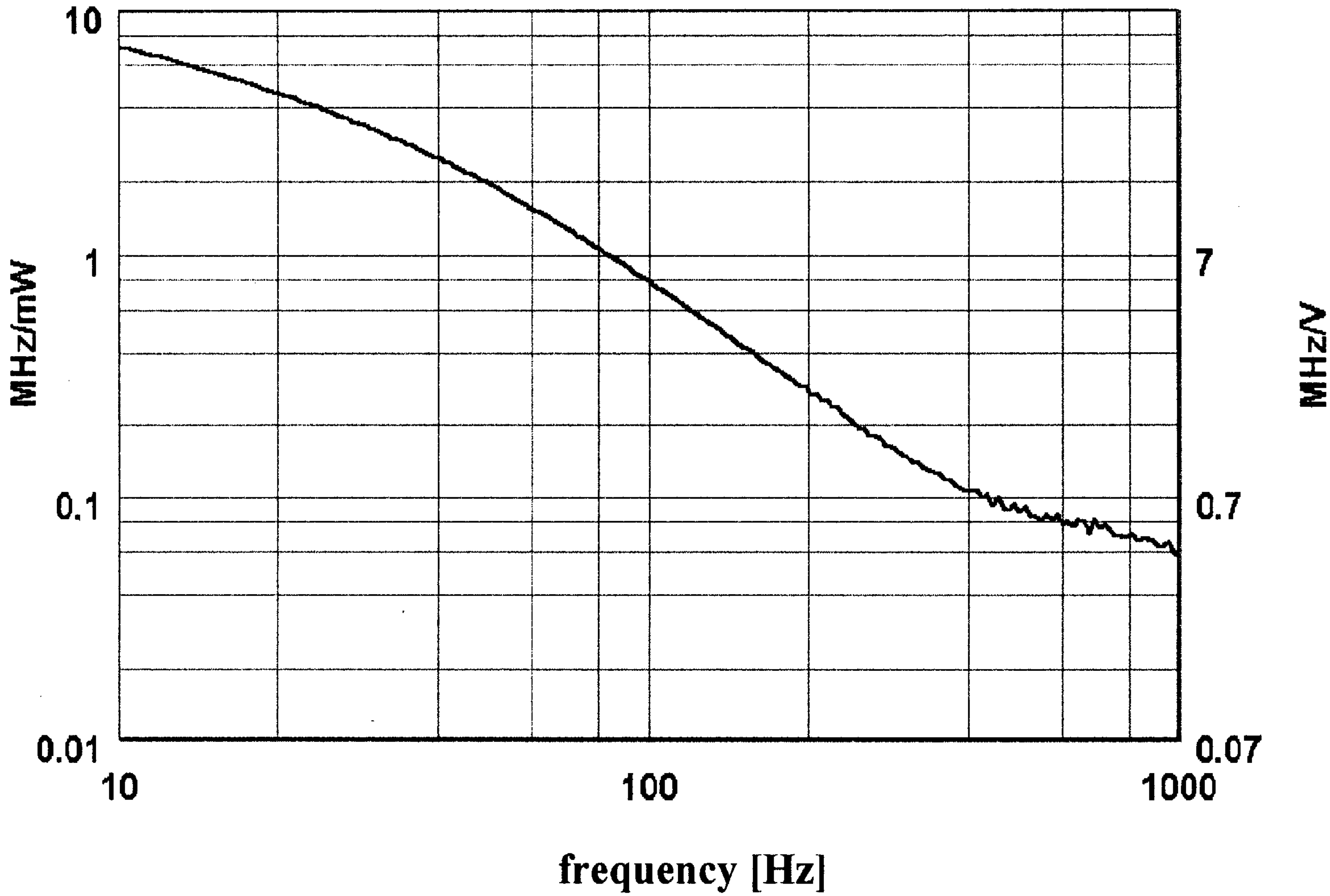




PMC#2 error point noise
PMC induced frequency noise limit required for being 25% below the PSL frequency noise requirement
PMC induced frequency noise limit required to meet PSL frequency noise requirements
6.25 kHz measurement, PMC Mk. II
100 kHz measurement, PMC Mk. II
6.25 kHz measurement, PMC Mk. I
PSL frequency noise requirement
frequency noise [Hz/√Hz]
frequency [Hz]

NPRO (700mW)

transferfunction power adjust - frequency



Data 09/04/97 scrn0001

cross- coupling

- changing the NPRO output power also changes the frequency of the NPRO

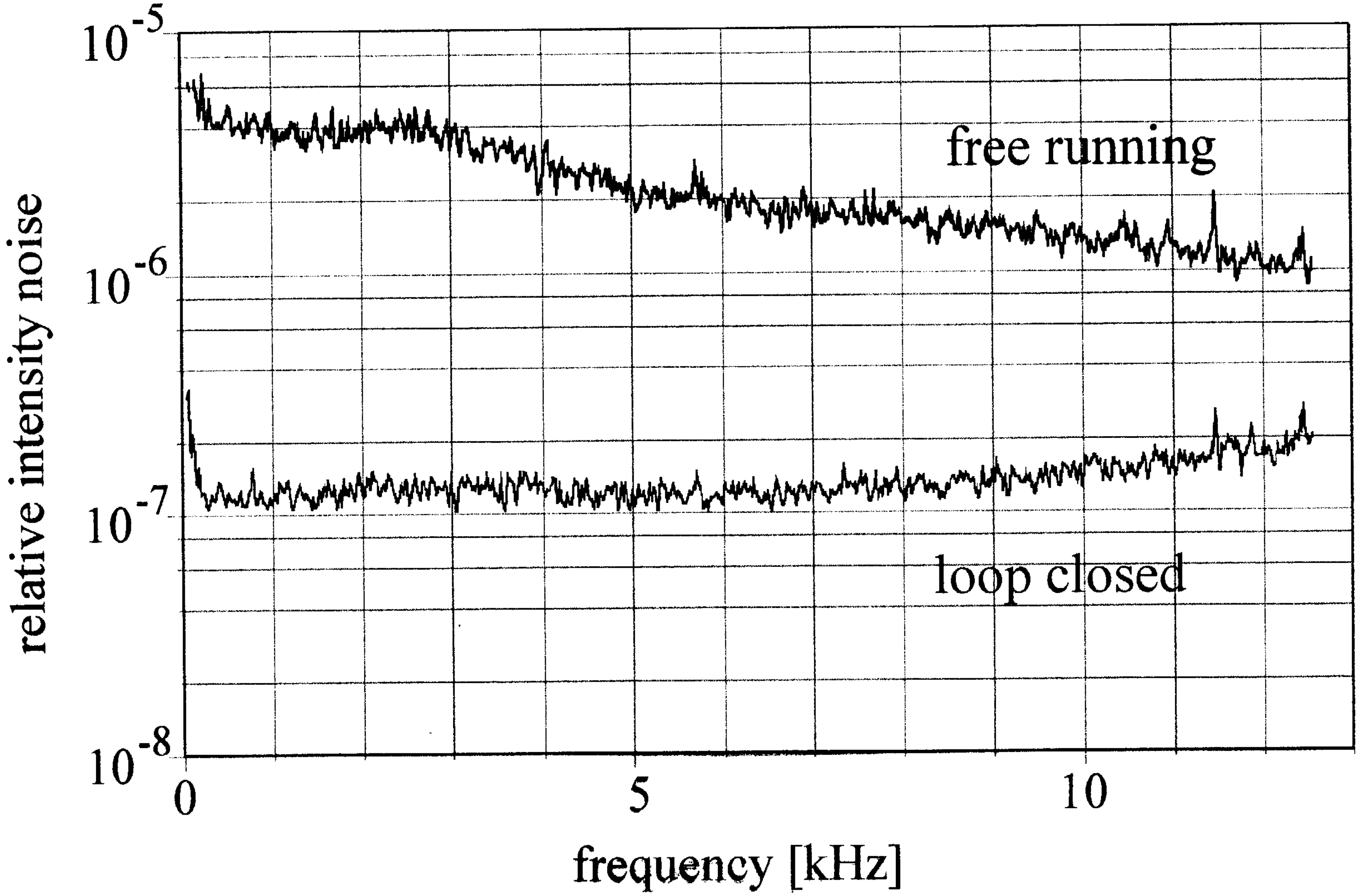
→ use only power adjust actuator of the power amplifier for the intensity stabilization loop

- "length noise" of the pre mode cleaner introduces phase noise of the 10W laser

→ increase the bandwidth and reduce electronic noise of the pre mode cleaner lenght control loop

10W Laser - RIN

free running and with split feed back loop



Data: 020398 ISS2.78D

NPRO - relative intensity noise

- assuming that the technical noise continues to fall like 1/f above 19MHz we get at 25MHz:

$$\delta I_{\text{tech, 75mW}} = 0.87\ \delta I_{\text{shot noise,75mW}}$$

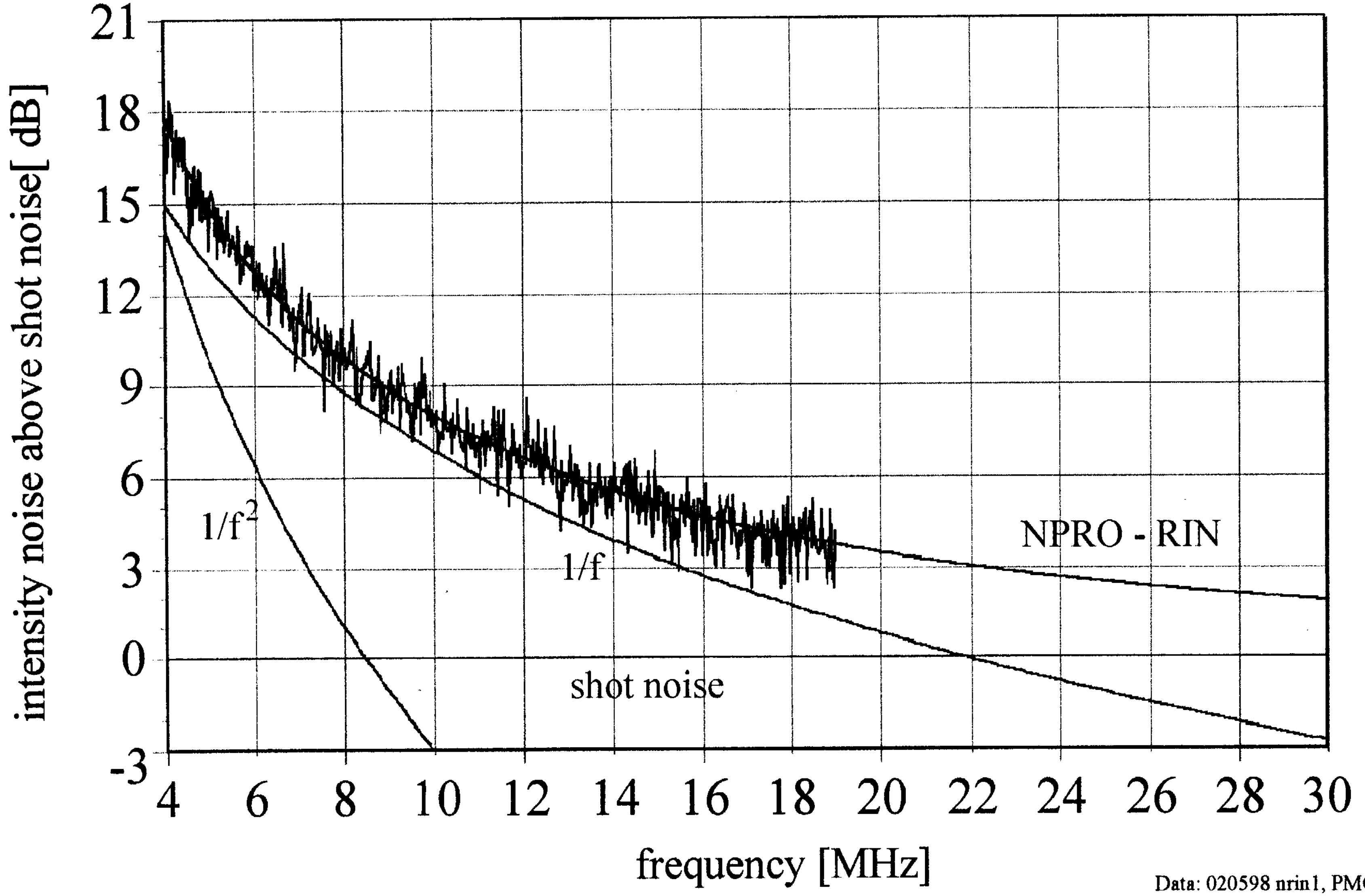
→ this corresponds to

$$\delta I_{\text{tech, 320mW}} = 1.82\ \delta I_{\text{shot noise,320mW}}$$

$$\delta I_{\text{320mW}} = 2.07\ \delta I_{\text{shot noise,320mW}}$$

NPRO - LIGO 10W Laser

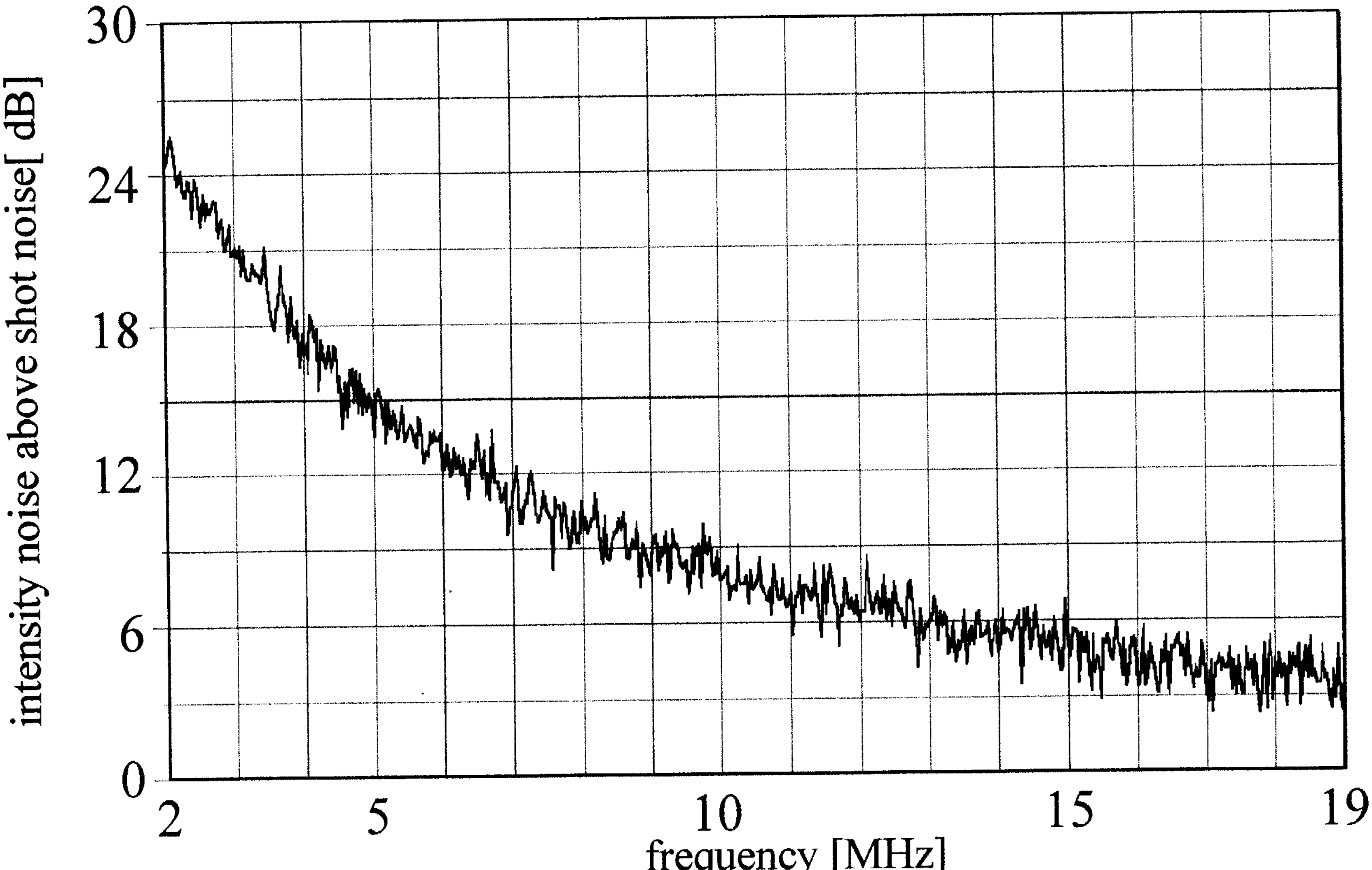
intensity noise relative to shot noise of 50mA



Data: 020598 nrin1, PMCrins2

NPRO - LIGO 10W Laser

intensity noise relative to shot noise of 50mA



Data: 020598 nrin1, PMCrins2

LIGO 10W laser - RIN measured

- for 100mA of detected photocurrent we measured :

$$\delta I_{\text{tech, 150mW}} = 1.6\ \delta I_{\text{shot noise,150mW}}$$

→ this corresponds to

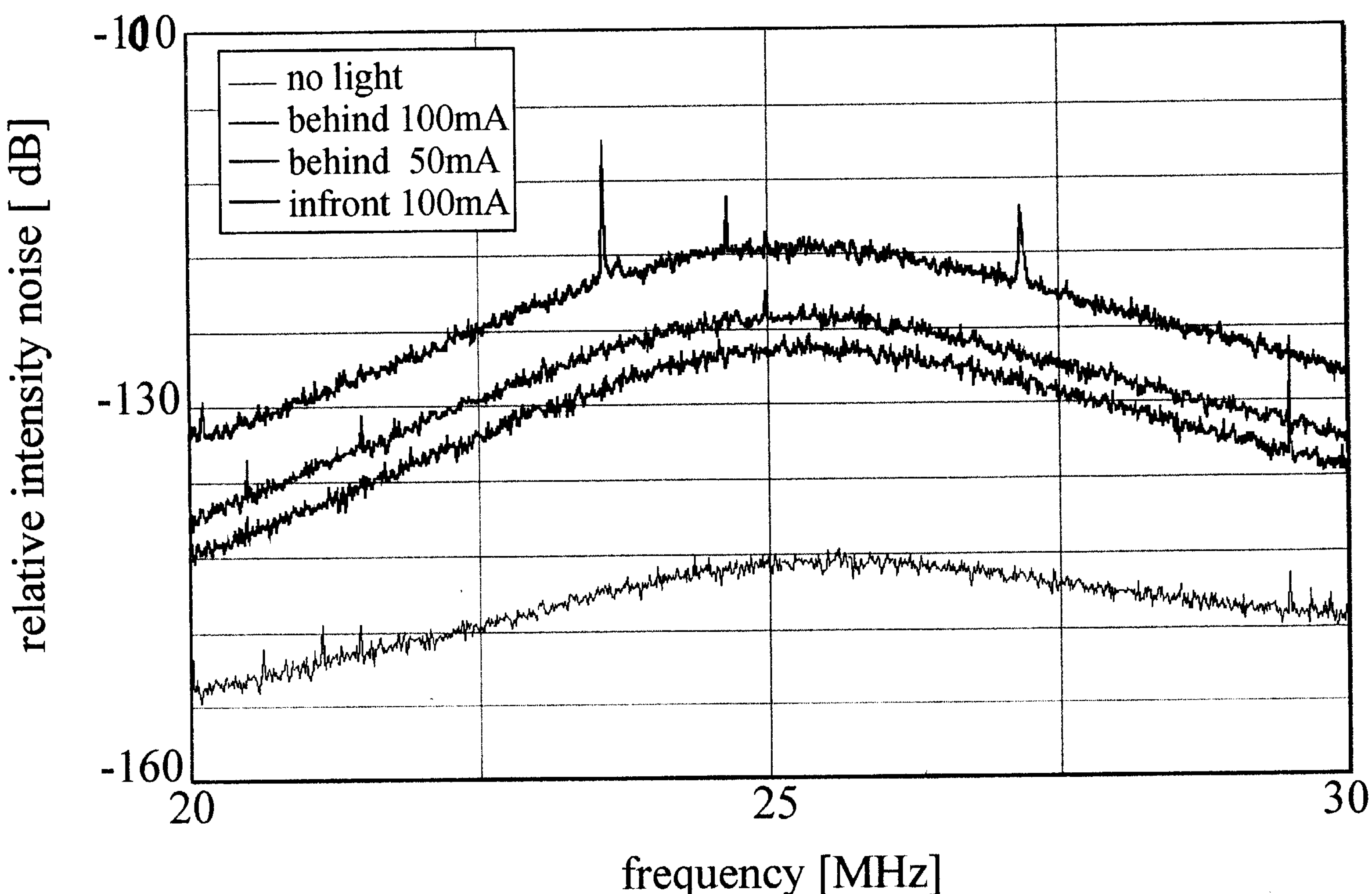
$$\delta I_{\text{tech, 10W}} = 13\ \delta I_{\text{shot noise,10W}}$$

→ to get the required technical noise filter factor of 31 we need :

pre mode cleaner FWHM = 800 kHz

LIGO 10 Watt Laser

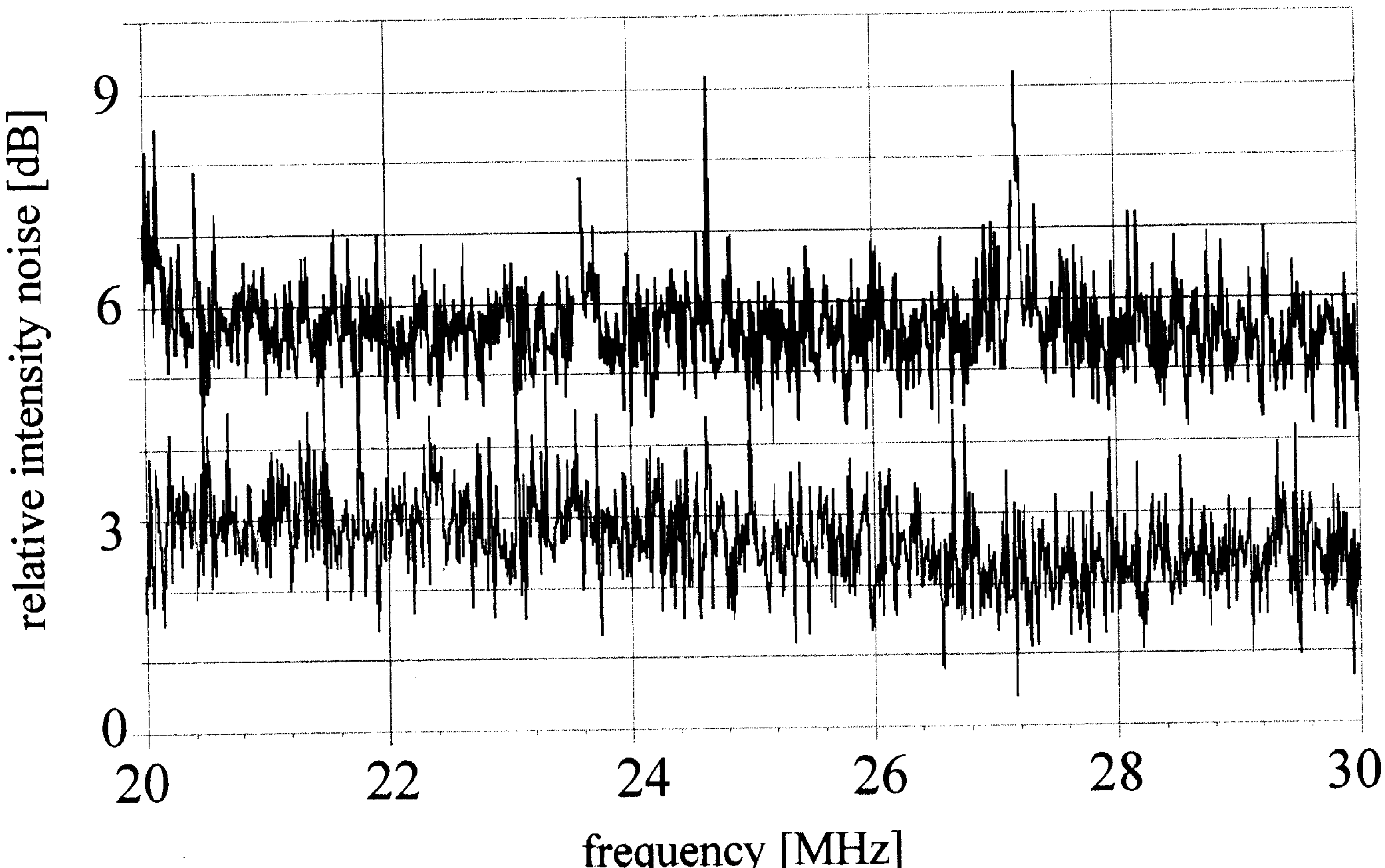
relative intensity noise infront and behind PMC



Data: 020598 modfrin1, 2 modfell

LIGO 10 Watt Laser

50mA compared to 100mA behind PMC
100mA, before PMC compared to behind PMC



Data: 020598 modfrin1, 2 modfel1

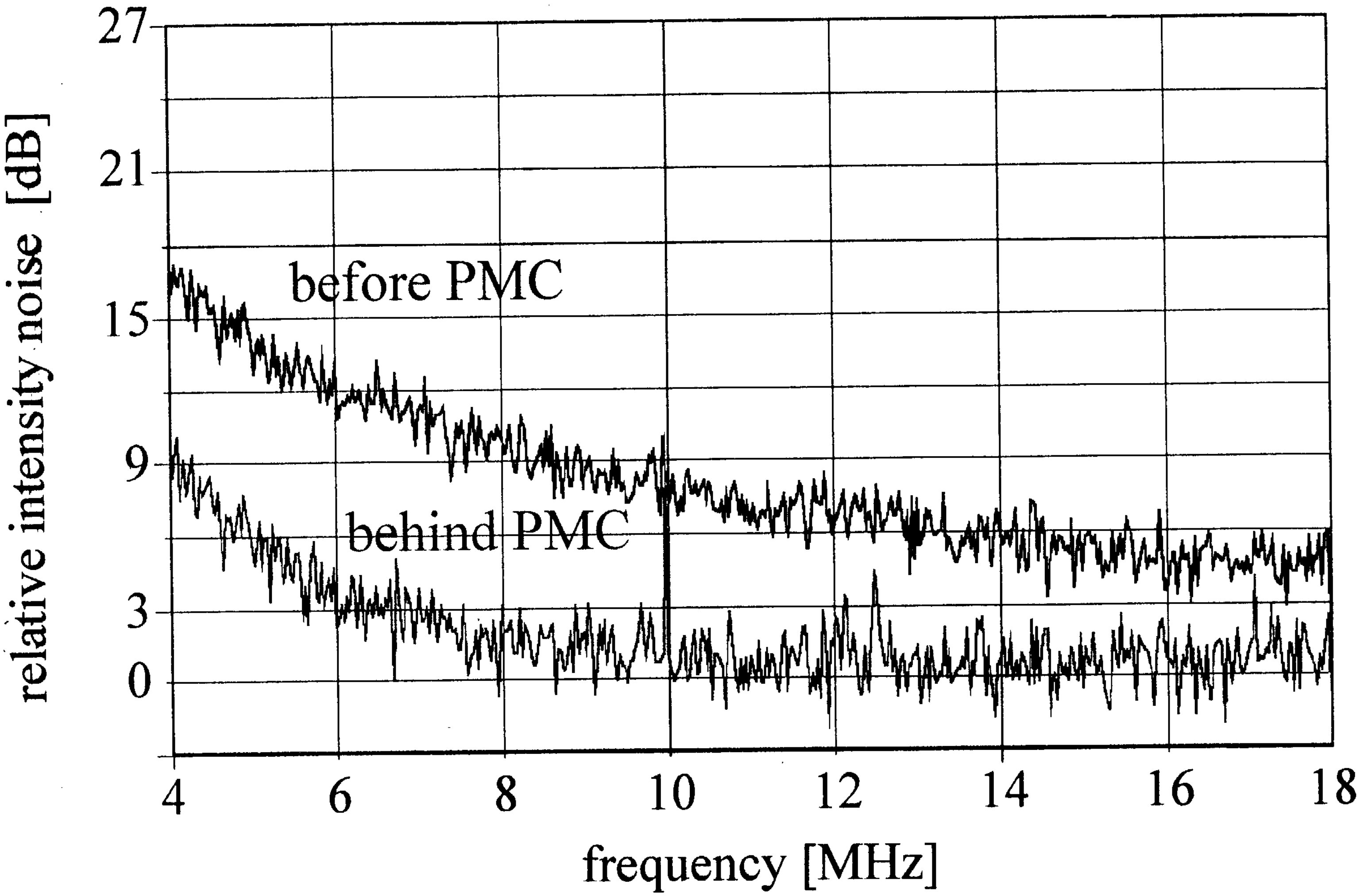
Agenda Lasers and Optics Working Group Meeting

March 12-14, 1998 Hanford Washington

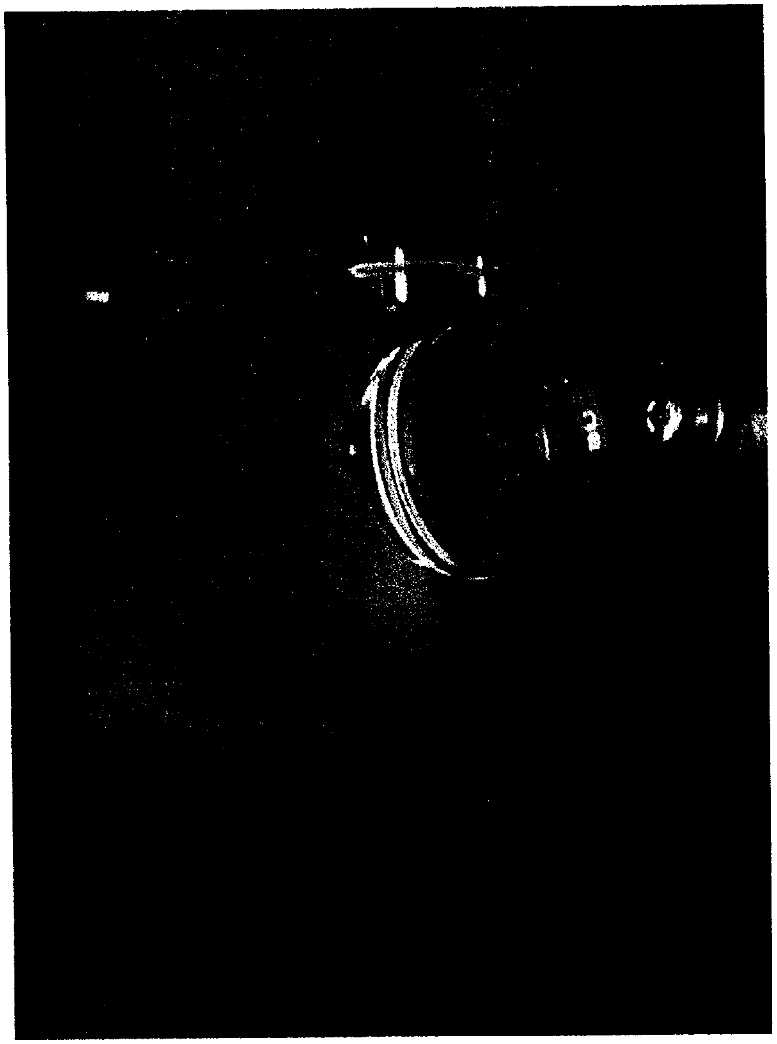
Friday 13 March 1998	Speaker	Start	Stop
A. Introduction	Rai Weiss	10:00 AM	10:10 AM
B. Core and Conditioning Optics and Photodetectors	Stan Whitcomb	10:10 AM	10:15 AM
1. LIGO Spec. setting and testing	Stan Whitcomb	10:15 AM	10:40 AM
2. The LIGO Optics testbed	Jordan Camp	10:45 AM	11:10 AM
3. Absorption Measurements	Alex Alexandrovsky	11:15 AM	11:40 AM
4. Contamination	Daqun Li	11:45 AM	12:10 PM
Lunch		12:15 PM	1:10 PM
5. LIGO Photodetectors and Testing	Alex Marin or Peter	12:15 PM	12:40 PM
6. LIGO Future Photodiode Needs	Mike Zucker	12:45 PM	1:10 PM
7. Deformable Optics and Wavefront Sensing	Justin Mansell	1:15 PM	1:40 PM
Break		1:45 PM	2:05 PM
C. The LIGO Pre-Stabilized Laser (PSL)	Rick Savage	2:05 PM	2:10 PM
1. PSL Overview - Lightwave laser	Peter King	2:10 PM	2:35 PM
2. Pre Mode Cleaner	Benno Willke	2:40 PM	3:05 PM
3. PSL Status and Plans	Peter King	3:10 PM	3:35 PM
D. Work on the NSF Advanced R&D Roadmap	Whitcomb/Savage	3:40 PM	5:10 PM
Dinner			
Saturday 14 March 1998			
E. Advanced Lasers	Peter Veitch	8:00 AM	8:05 AM
1. The future of Lasers for LIGO	Robert Byer	8:05 AM	8:30 AM
2. GEO Laser	Benno Willke	8:35 AM	8:55 AM
3. ACIGA Laser Progress	Peter Veitch	9:00 AM	9:20 AM
4. ACIGA Laser Proposed	Damien Mudge	9:25 AM	9:45 AM
5. Slab Amplifier and Amplifier Noise	Todd Rutherford	9:50 AM	10:10 AM
6. The prospects for new wavelengths	Marty Fejer	10:15 AM	10:40 AM
F. Work on the NSF Advanced R&D Roadmap	Eric Gustafson	10:45 AM	12:15 PM

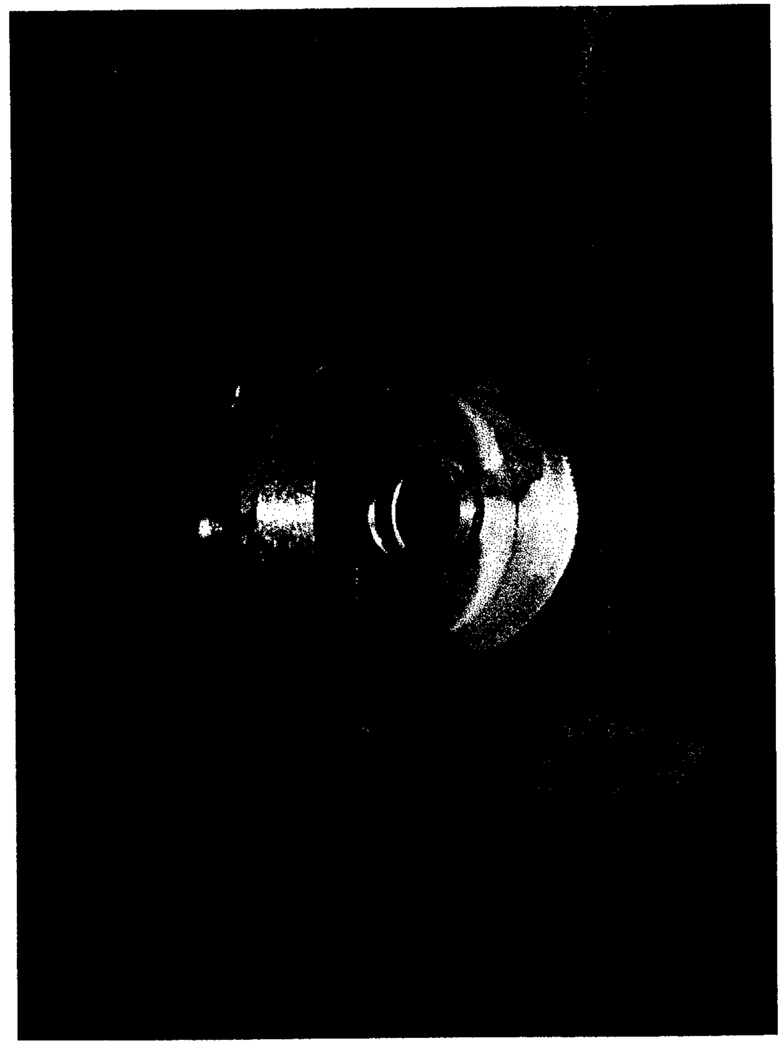
10W Laser - PMC filtering

intensity noise relative to shot noise of 50mA

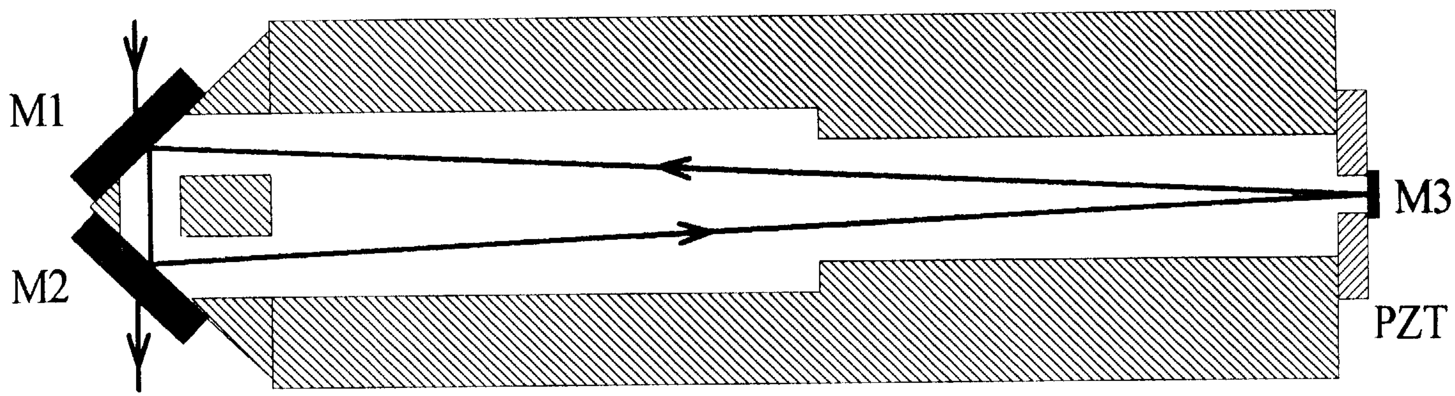


Data: 020598 PMCRIN4, arin3



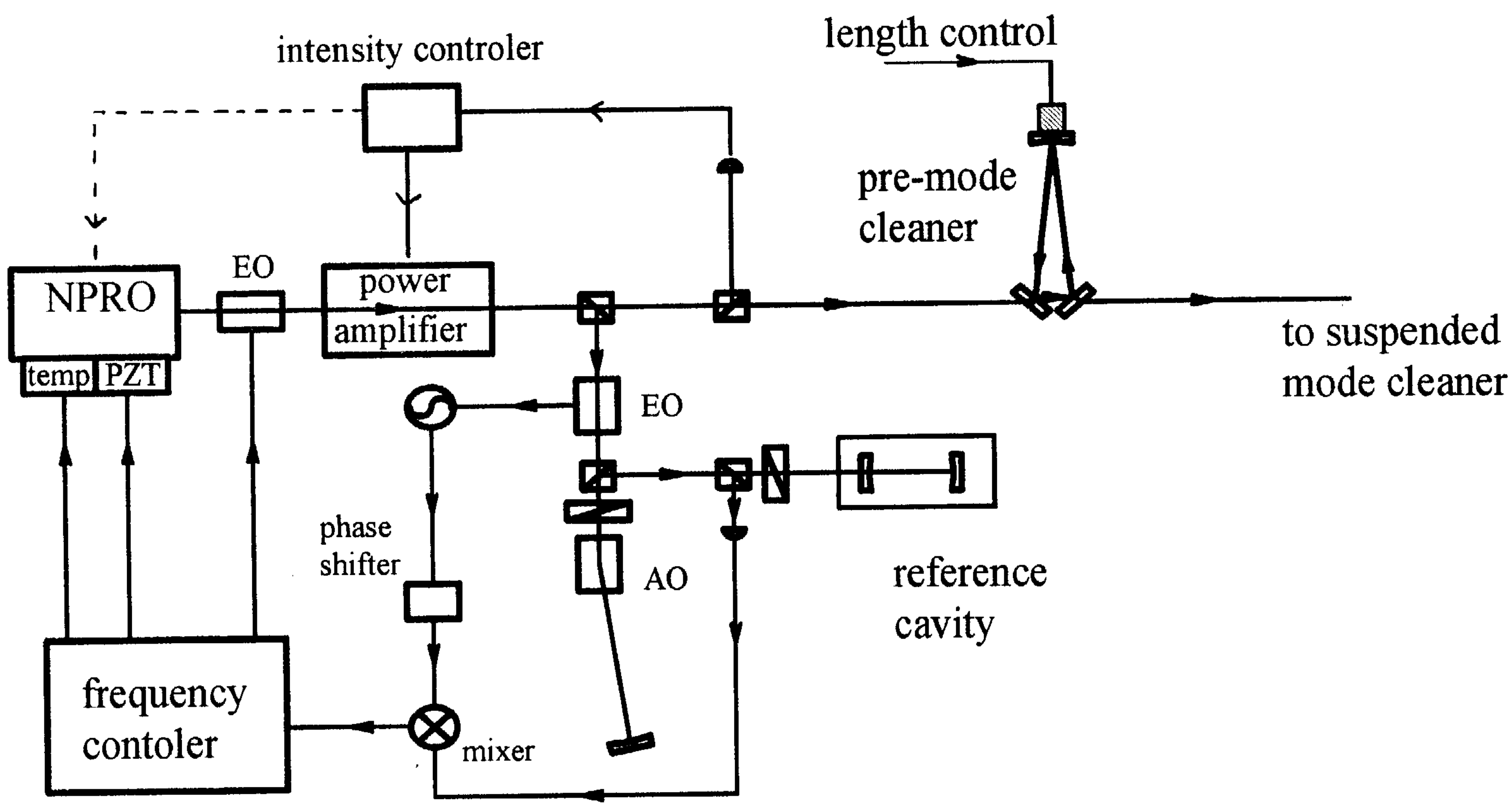


Stanford pre-mode cleaner



- 713 MHz free spectral range
- linewidth: 170 kHz in s-pol. , 3.3 MHz in p-pol.
- power transmission: 95% in s-pol. , 99 % in p-pol
- 99 % mode coupling (300mW NPRO)

pre-stabilized LIGO 10W laser



LIGO 10W laser - RIN calculation
(PSL conceptual design study)

- assumptions :
  - the NPRO is shot noise limited at 25MHz
  - amplifier gain H = 20

→ $\delta I_{\text{tech, 10W}} = 6\ \delta I_{\text{shot noise,10W}}$

- the pre mode cleaner needs to filter the technical laser intensity noise at 25 MHz by a factor of 15

→ pre mode cleaner FWHM = 1.6 MHz

LIGO intensity noise requirements

- heterodyne techniques are used to transfer the gravitational wave signal into the MHz band

→ intensity noise at the modulation frequency limits the detector sensitivity

- LIGO pre stabilized laser goal (at 25MHz):

$$\delta I_{600mW} = 1.005 \ \delta I_{shot\ noise,600mW}$$

$$\delta I_{tech,\ 10W} = 0.4 \ \delta I_{shot\ noise,10W}$$

Note 1, Linda Turner, 04/20/98 06:22:08 PM
LIGO-G980049-23-M