A Path to LIGO II

Lasers - ANU, Lightwave, LIGO and Stanford

- Requirements
- Potential Designs

Ancillary Optics - LIGO/Florida

- Phase modulators
- Optical isolators
- Telescopes
- Mode Cleaner

Thermal Modeling - Beausoleil, Florida, GEO, LIGO and Stanford

Adaptive Optics - LIGO/MIT, Stanford

Lasers and Optics Working Group Milestones

Materials for Core Optics and Beam Splitters

- Growth
- Figuring & Polishing
- Evaluation
- Fabrication

Conclusion

SCANNED

LIGO Scientific Collaboration Lasers and Optics Working Group

LIGO-G990058-00-R

Old LIGO II Laser Requirements

Amplitude Noise

10^{-8} [1/√Hz] (100 Hz) 10^{-8} [1/√Hz] (1khz)

Frequency Noise

10^{-8} [Hz/√Hz] (100 Hz) 10^{-8} [Hz/√Hz] (1khz)

Amplitude of higher order modes

$4x10^{-8}$ [1/√Hz] (100 Hz) $4x10^{-8}$ [1/√Hz] (1khz)

Power 50 - 200 [Watts]

Laser Design Alternatives

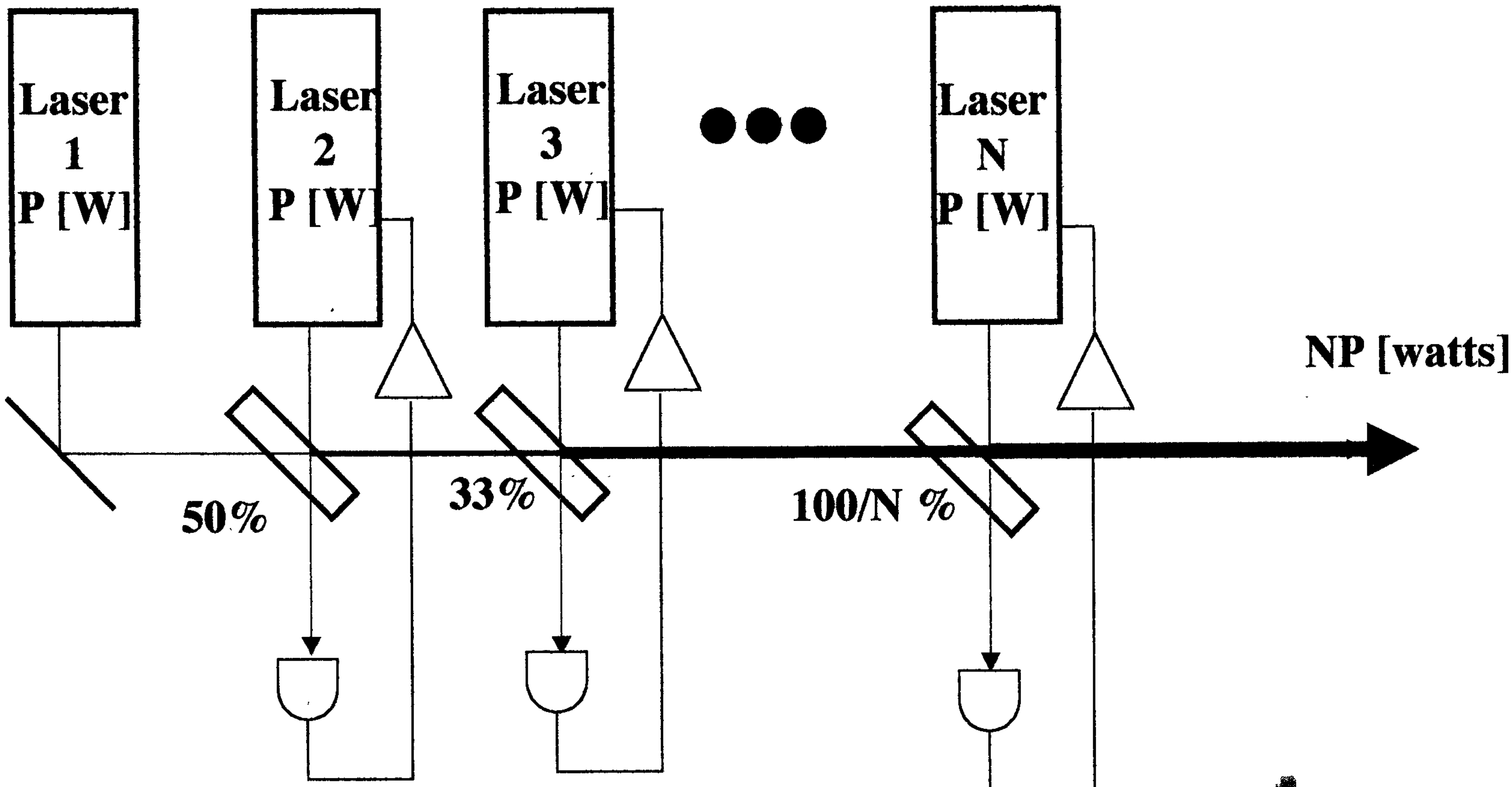
<u>LIGO I - 10 watts</u>
Lightwave 10 Watt Master Oscillator Power Amplifier

<u>LIGO II - 100 watts</u>
Coherent addition or injection chaining

Injection Locked Unstable Resonator Nd:YAG - 100 watt

Power Amplifier for LIGO I Laser to 100 watt "class"

Power - Coherent Summation



Kerr, G.A., Hough J Applied Physics B, Vol. B 49, No. 5, p. 491-495, Nov. 1998

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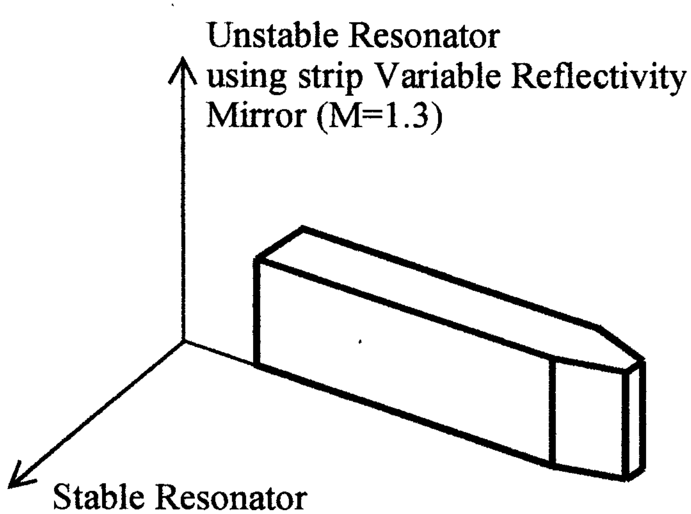
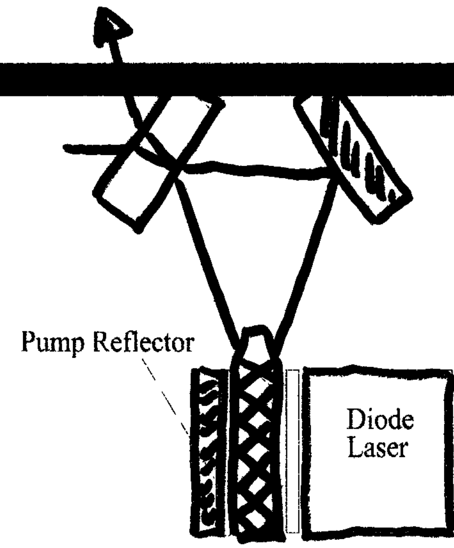
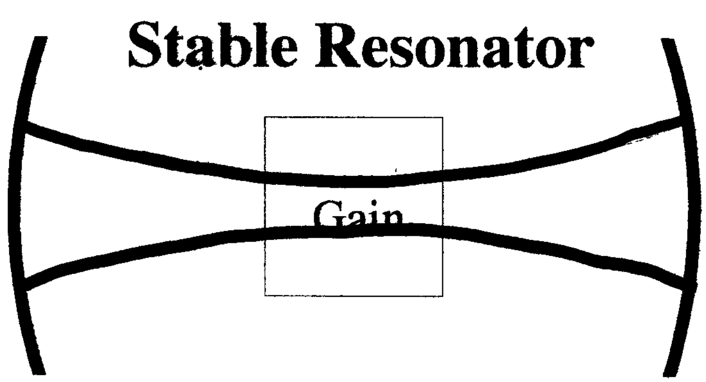
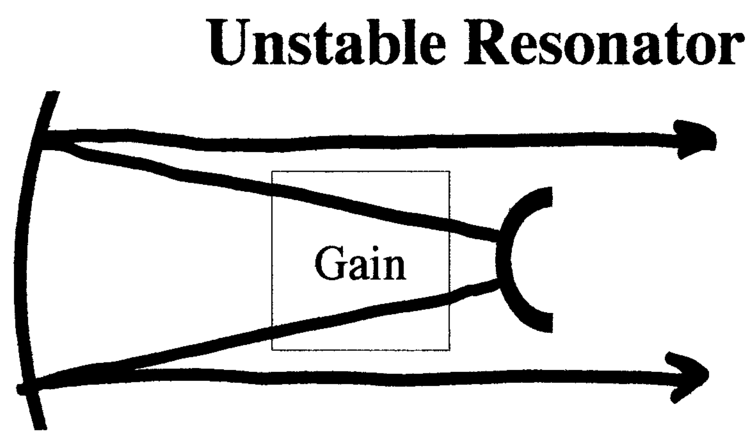
Power - Unstable Resonator





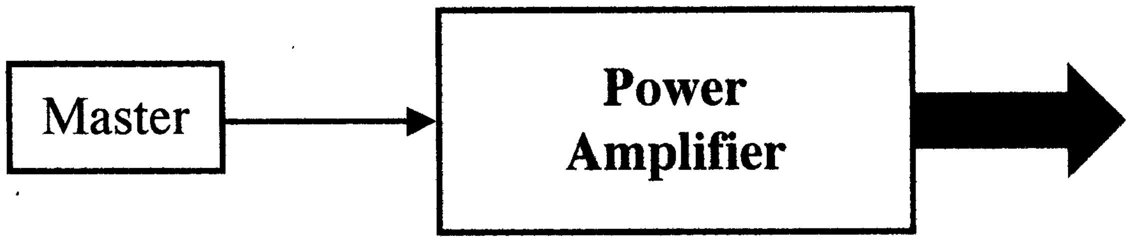




Siegman

Power - MOPA

Master oscillator power amplifier



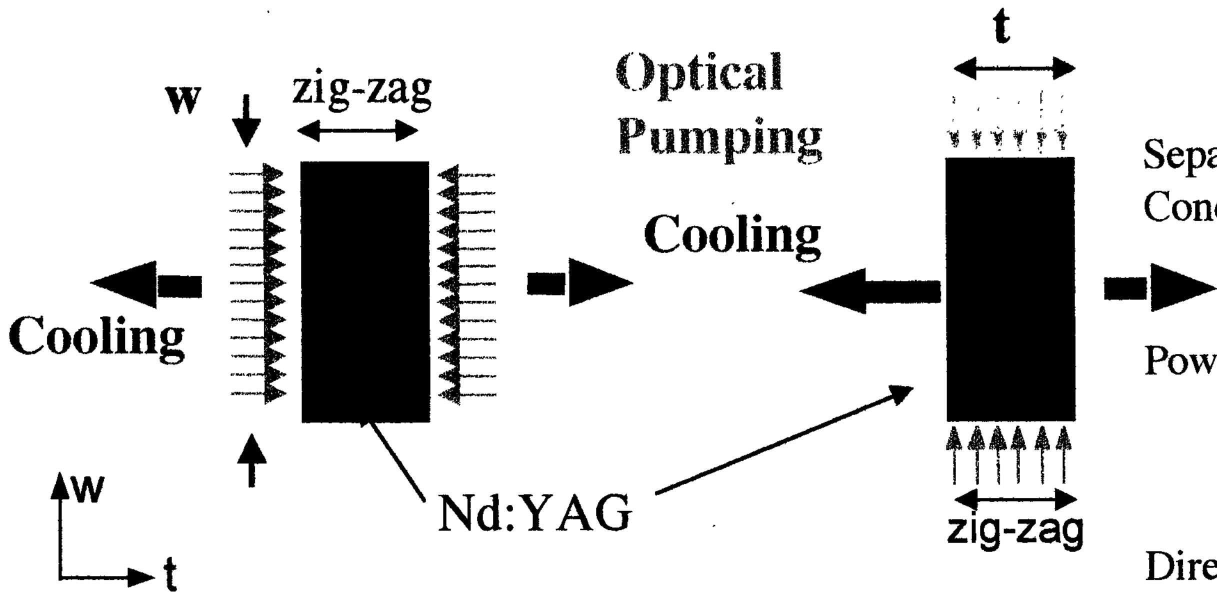
Technical Challenges

Power Noise
(Filtered by pre-mode-cleaner)
Extraction Efficiency
(Operate > saturation
intensity)

Advantages

Scaleable
No optical resonances
Coherence Control
Soft failure mode
Modular

Power - Face versus Edge Pumping



- Separate pumping and cooling interfaces
- Conduction cooling
  - No fluid on optical surfaces
  - Mechanical stability
- Power Scaling Advantage
  - Increase aspect ratio
    - Improve pump absorption
    - Increase cooled area
- Direct coupling of pump fibers
  - Efficient, robust

Face - Pumped

Cooling face = Pumping Face

Stress fracture (w/ t)

Pump Absorption t

Edge - Pumped

Cooling face ≠ Pumping Face

Stress fracture (w/ t)

Pump Absorption w

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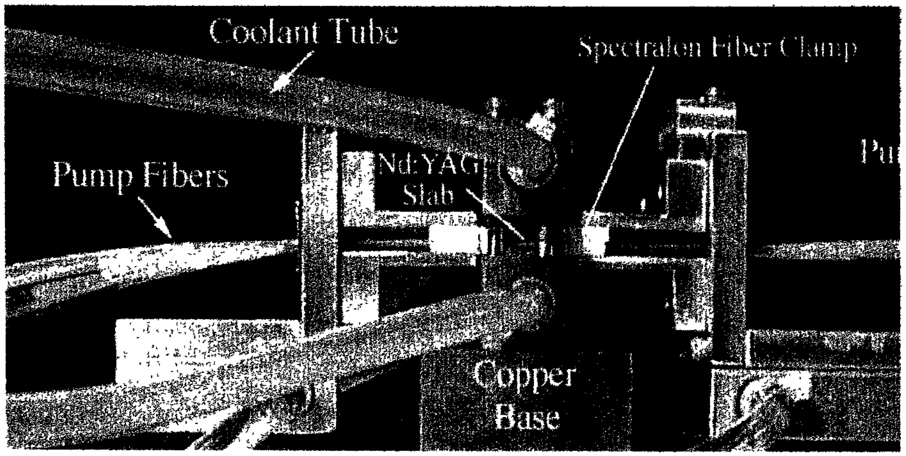
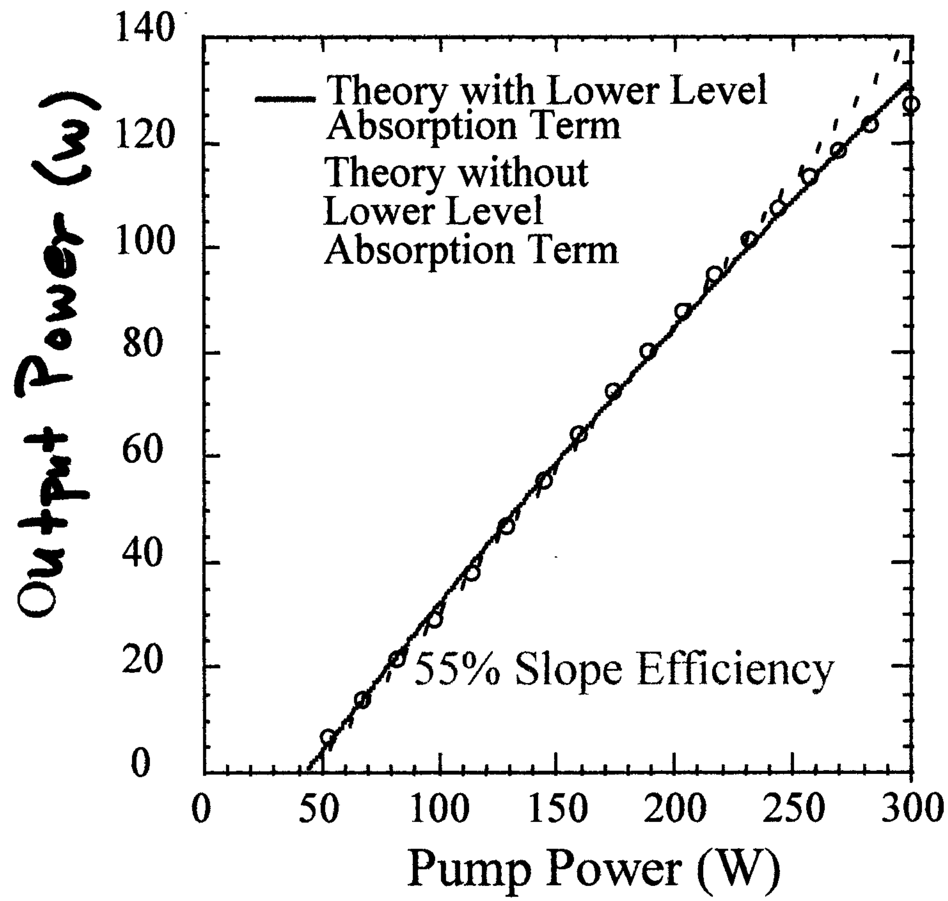
Edge Pumped Slab Oscillator





- **3:1 Aspect Ratio Nd:YAG Slab**
  - 1.5 x 4.5 x 38.9 mm w/ Brewster end faces
  - SiO_2 Coating for low loss TIR
  - 1.5 % single-pass loss
- **95% Pump Absorption Efficiency**

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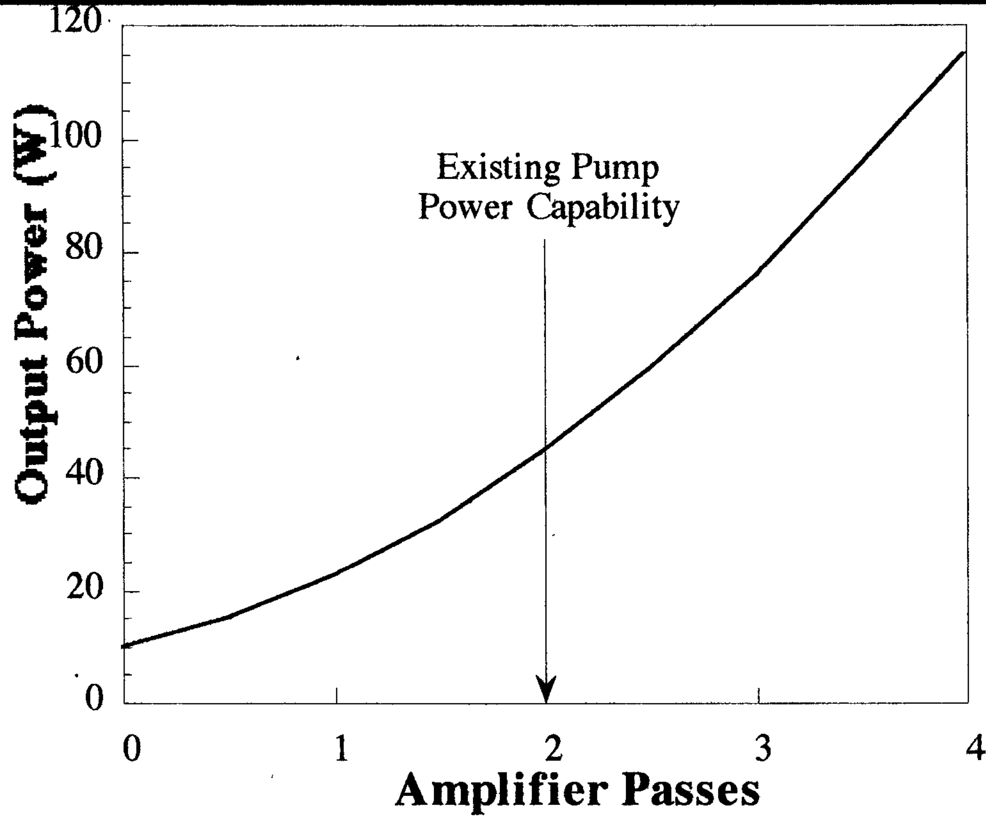
Master Oscillator Power Amplifier



First Double-Pass Amplifier | Second Double-Pass Amplifier

Master Oscillator
- 10 W LIGO Laser

Amplifier
- Edge-Pumped
- Conduction-Cooled
- Double-Pass
- 300 W Fiber-Coupled Laser Diode Arrays

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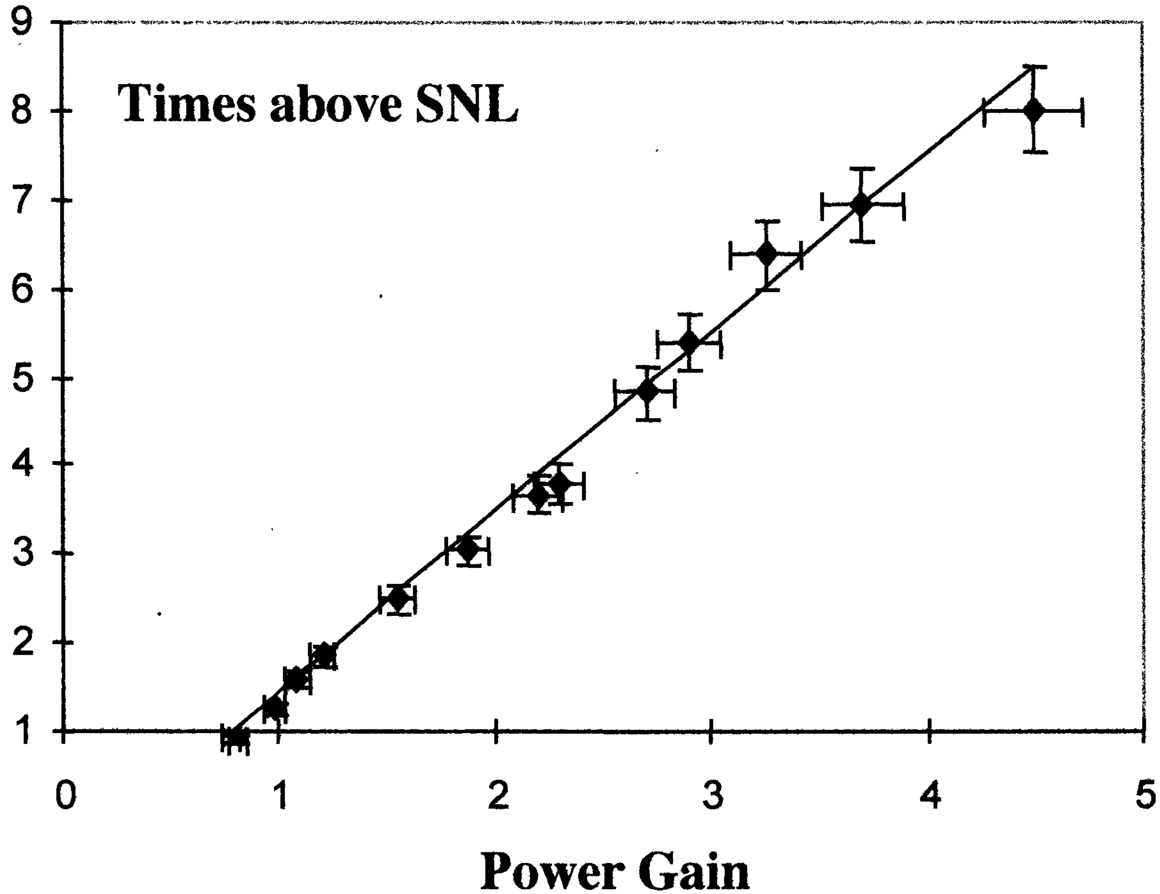
MOPA Power Fluctuations



Amplifier Noise Theory

$$\frac{\sigma^2}{\sigma^2_{Shot}} = 1 + 2\,\eta\,\eta_{sp}\,(G-1)$$

Tulloch, W.M. et al. Opt. Lett., Vol. 23, No. 23, Dec. 12, 1998

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Ancillary Optics

Phase Modulators

Optical Isolators

Mode Cleaners

Telescopes

Electro Optic Modulator Requirements

Requirement	LIGO I	LIGO II	Consequences
Power	10 W	100 W	Thermal focussing, Depolarization, Damage!
Modulation Frequency	<100 MHz	<100 Mhz	Piezoelectric Resonances
Modulation Depth	0<G<1	0<G<1	Higher order sidebands
RF Amplitude modulation	$<10^{-3}$	$< 10^{-3}$	Alignment

Thermal Modeling

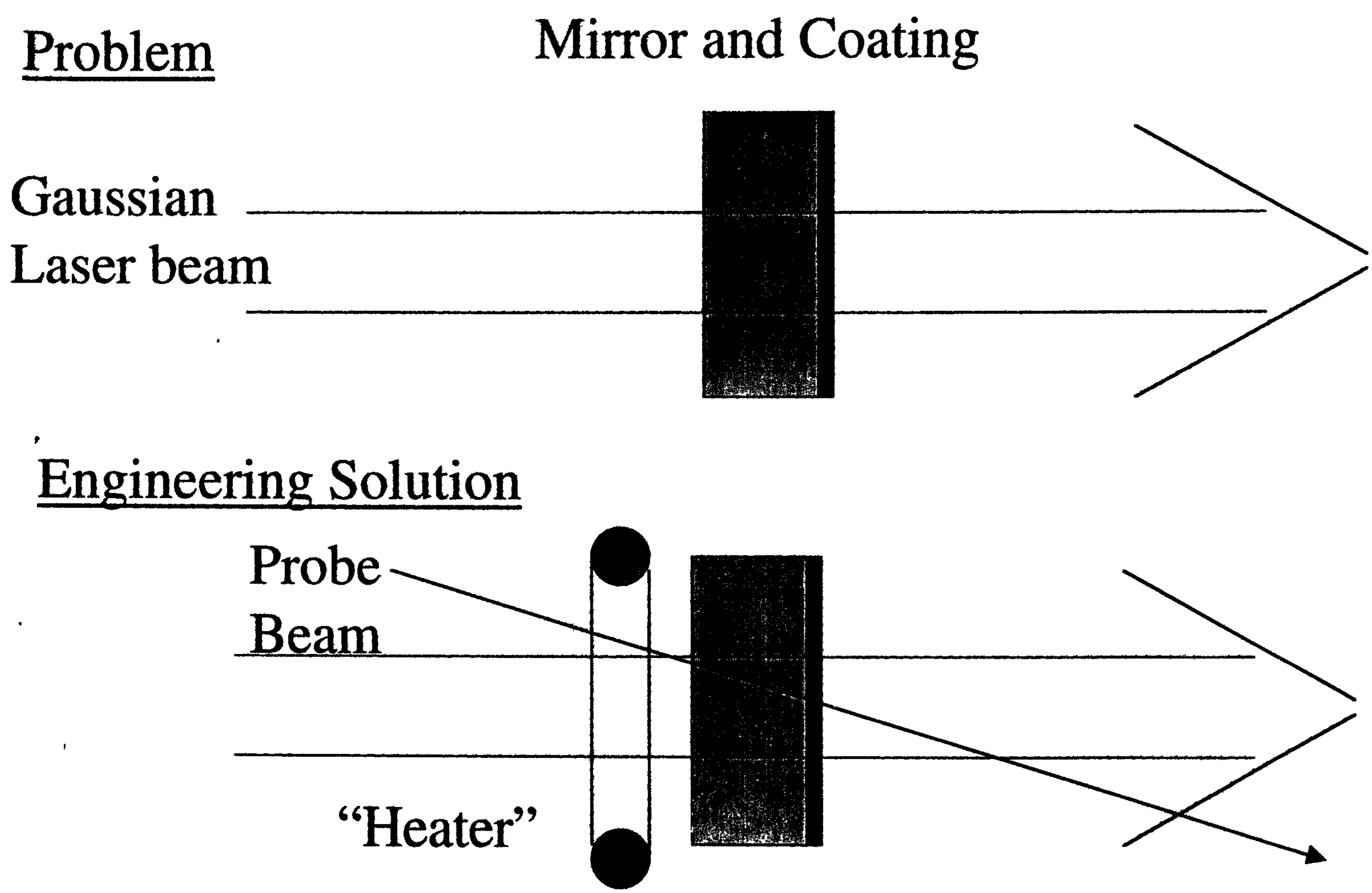
MELODY Package - Ray Beausoleil

Optical modal model including thermal focussing in core optics and beamsplitter

LIGO I, GEO I, Dual recycling

Validation underway

Adaptive Optics



Lasers and Ancillary Optics Milestones

Top-Level requirements review	1Q99
Design summit	3Q99
Preliminary design review	1Q00
Component prototypes	1Q01
Fabricate engineering prototypes	1Q02
Final design review	1Q03
Fabrication complete	4Q03
Installation complete	2Q04
Commissioning	4Q04

Desirable properties for core optic material

Low thermal noise

- Low mechanical loss
- High density
- High speed of sound

Low thermal distortion of laser light

- Low optical absorption
- Low dn/dT
- Low coefficient of thermal expansion
- High thermal conductivity
- High heat capacity

Must also be :

Available in suitable sized pieces

Capable of being figured and polished to high specs

Materials Evaluation

Bulk absorption - Blair, Boccara and Fejer

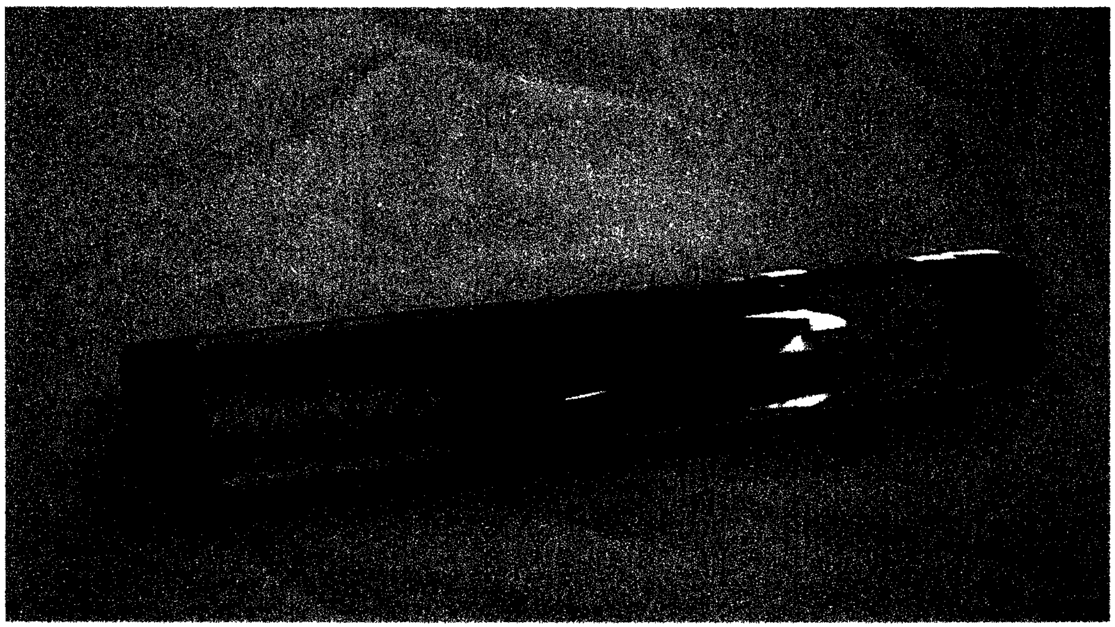
Surface figure - Caltech LIGO

Micro roughness and scatter - Caltech LIGO

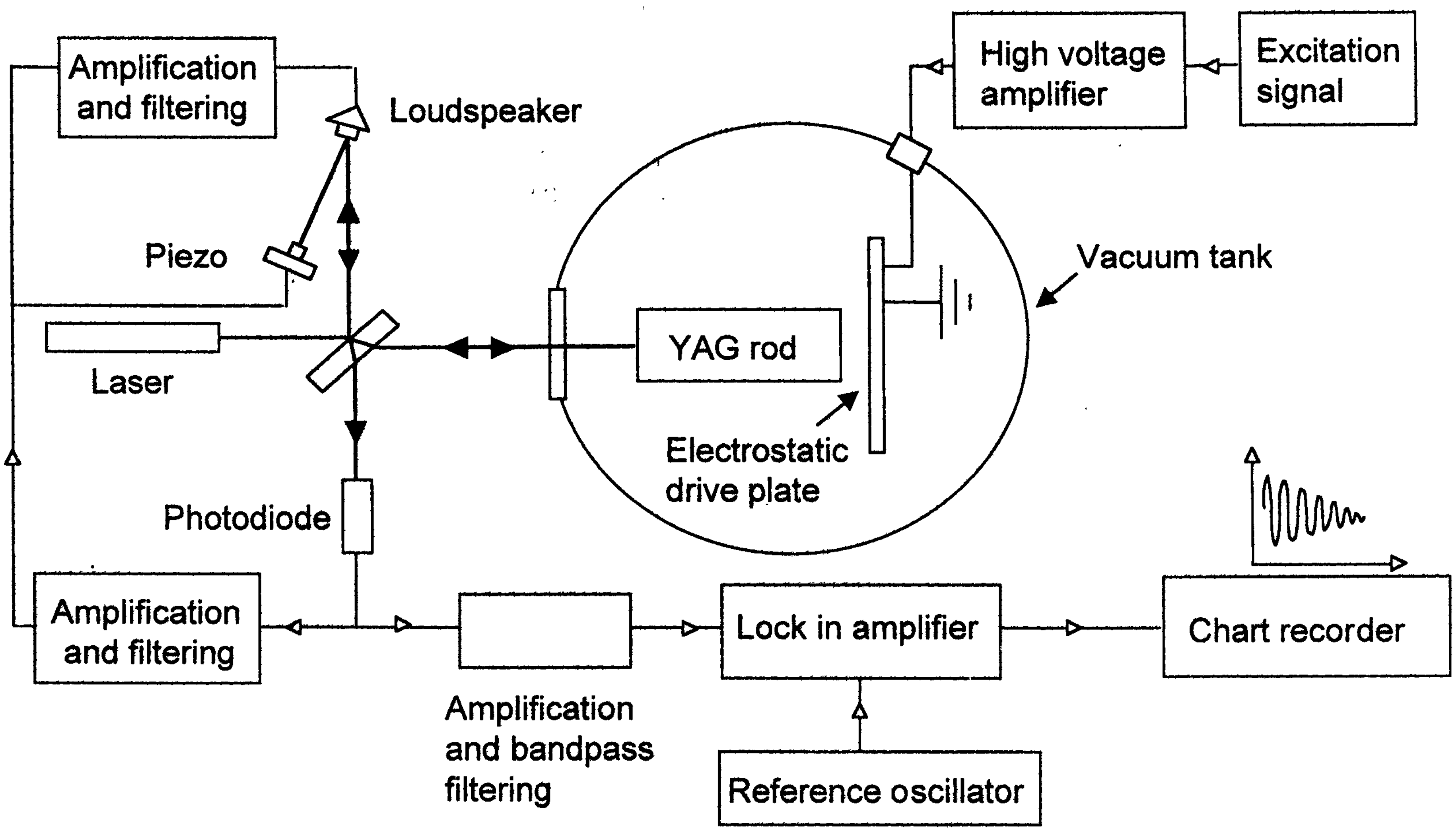
Coating absorption - Bocarra and Fejer

Mechanical loss of YAG

- Fabricate cylinder of YAG , dimensions:
  2.5 cm diameter, 10.2 cm long
- Frequency of fundamental longitudinal mode: 38.9kHz



Measurement technique



Results and interpretation

- Q of fundamental longitudinal mode (10 ringdowns):

  $(2.18 \pm 0.03) \times 10^{7}$

  i.e. mechanical loss $(4.59 \pm 0.03) \times 10^{-8}$

- Possible interpretations:

  (a) Limited by losses associated with suspension system e.g. frictional losses at breakaways

  - Next stage - suspend sapphire sample of higher (known) Q in system - check for presence of excess loss

Comparison with fused silica, sapphire and silicon

	Fused Silica	Silicon	Sapphire	YAG
↑ Density, r (kgm^{-3})	2.2×10^3	2.33×10^3	3.98×10^3	4.55×10^3
↑ Speed of sound, c (ms^{-1})	5720	8415	10025	7887
↓ dn/dT (K^{-1})	8.7×10^{-6} *	-	1.36×10^{-5} *	7.3×10^{-6} *
↓ Coeff. Therm. Exp. α (K^{-1})	5.1×10^{-7}	2.62×10^{-6}	7.15×10^{-6}	7.7×10^{-6}
↑ Spec. Heat Cap., C_m ($J\,kg^{-1}K^{-1}$)	746	713.9	777	625
↑ Thermal Cond., K ($Wm^{-1}K^{-1}$)	1.38	140	25-35	13

All data taken from "Electro- optics handbook", Eds. R. Waynant, M. Ediger, Pub. McGraw Hill apart form
* "Optical materials" S. Musikant, Pub. Marcel Dekker Inc (1985)
Properties specified at 300K

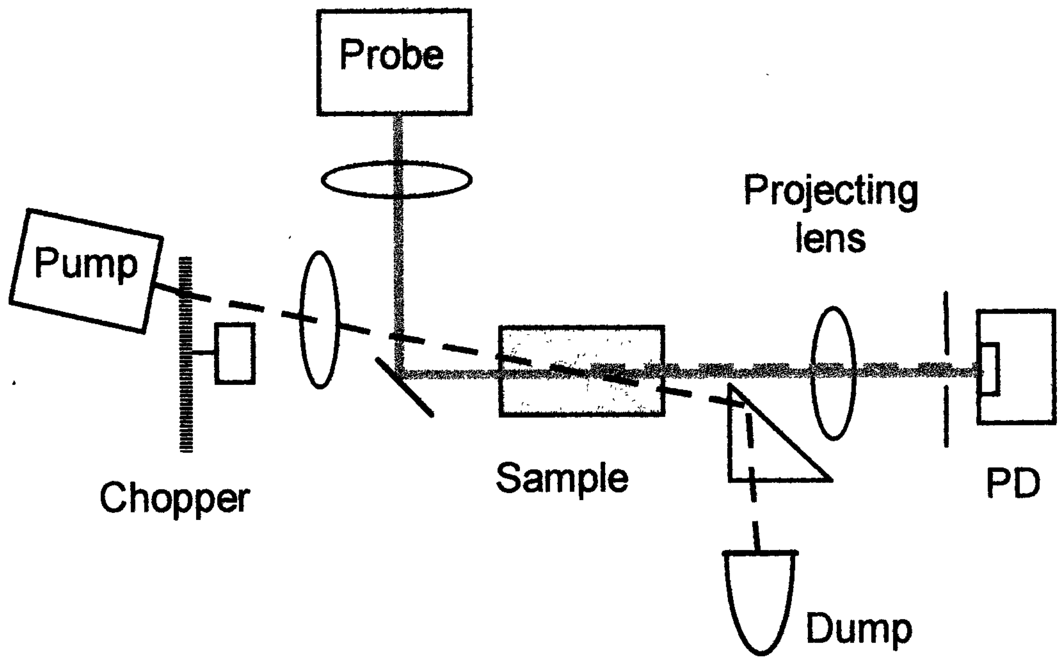
Materials Processing

Figuring - Caltech LIGO

Polishing - Caltech LIGO

Suspension Attachments - GEO and Stanford

Photothermal Common-path Interferometer (PCI)

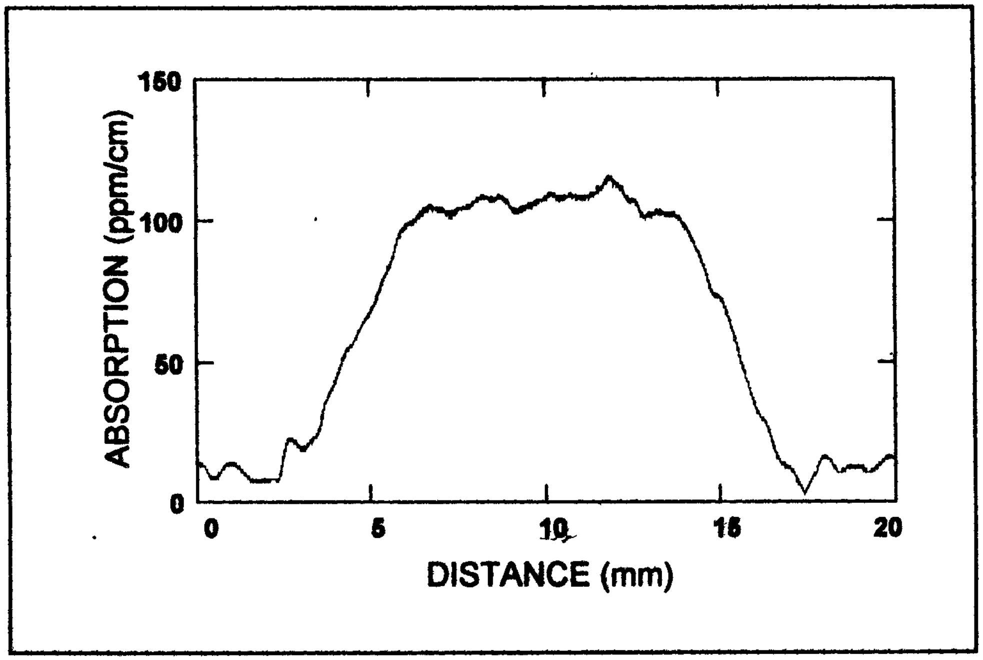


Pump waist	50 μ	Chopping frequency	380 Hz (10Hz - 2 kHz)
Probe waist	120 μ	Crossing angle	1° - 20° (in air)
Pump power	5 W	Probe power	0.5 mW

- **ac-component of probe distortion is detected by photodiode + lock-in**
- **absorption coefficient of 10^{-7} cm^{-1} can be detected with a 5 W pump**
- **crossed-beams help to avoid false signals from optics and surfaces of the sample**

Absorption in pure YAG

Absorption at 1064 nm, scan from surface to surface



- $10x10x10mm^3$ cube
- uniform bulk absorption of 105 ppm/cm ± 10%
- normalized to Ti-sapphire reference with a correction for different dn/dT and thermal conductivity

Core Optics and Beamsplitter

Fused Silica -

Sapphire - Crystal Systems

a-axis 1M$/ year for 5 years

c-axis 2/m$/ year for 5 years

YAG - Scientific Materials - ?

GGG - Litton Airtron - 2 years - 2M$?

Silicon - Several growers - 10 inch optic -10K$

Near Term Lasers and Optics Milestones

Set laser requirements after suspensions design summit

Set adaptive core optic control requirements after suspensions design summit

Select laser design at July 1999 LSC meeting

Set modulator requirements at July 1999 LSC meeting

Design a materials development program at the July LSC meeting

Lasers and Optics Design Summit

July 1999 LSC Meeting

Lasers, Ancillary Optics, Adaptive Optics - 1 day
- Agree on requirements
- Invite laser vendors

Materials Issues - 1 Day
- Make a plan for the materials development
- Invite crystal growth vendors

Conclusion

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- Phase modulators
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Thermal Model - Beausoleil, Florida, GEO, LIGO and Stanford

Adaptive Optics - LIGO/MIT, Stanford

Milestones and Schedule

Materials for Core Optics and Beam Splitters

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