Presentation to the Special Emphasis Panel

LIGO Lasers and Optics Working Group

Eric Gustafson

Outline

Goals
Organization and the 6 Subgroups
Interferometer Materials Map
Thermal Distortions and Modeling
The 6 Subsystems
Backup
Conclusion

Goals

Radiation pressure noise equal to the sum of all other noise sources at 10 Hz for 30 kg mirrors

700 kw of circulating power in the arms.

Power recycling factor of 50

Arm cavity Finesse 200

Laser power 180 watts

Subgroups within the Lasers and Optics Working Group

Mode Cleaners & Telescopes
Tanner (LIGO/Florida)

Modulators and Isolators
Reitze (LIGO/Florida)

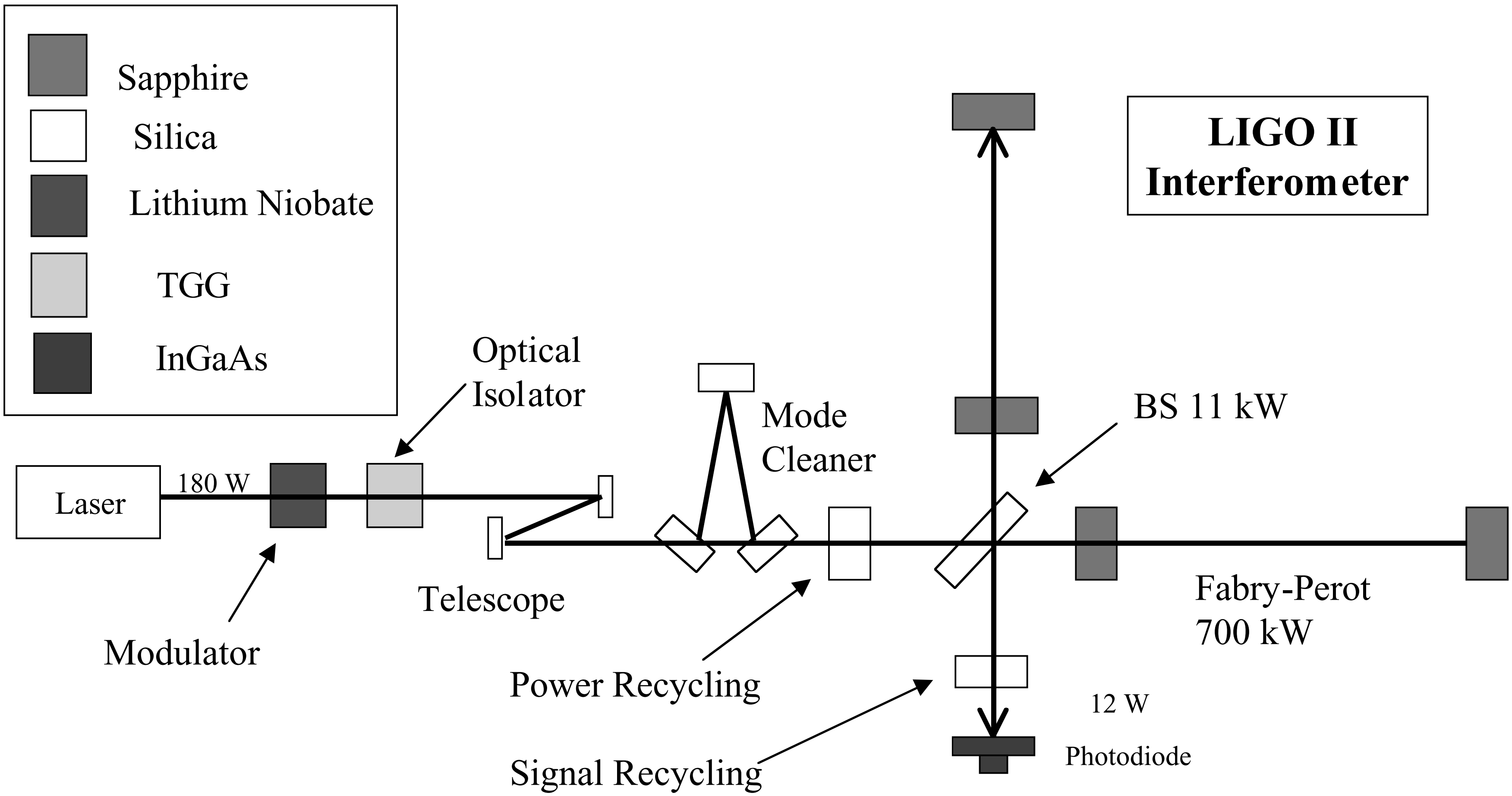
Photodiodes
Specifications and Testing -
Zucker (LIGO/MIT)
Fabrication - Harris (Stanford)

Lasers and PSL
Camp (LIGO)
Byer (Stanford), Munch (Adelaide)
Savage (LIGO/Hanford), Willke (GEO/Hanover)

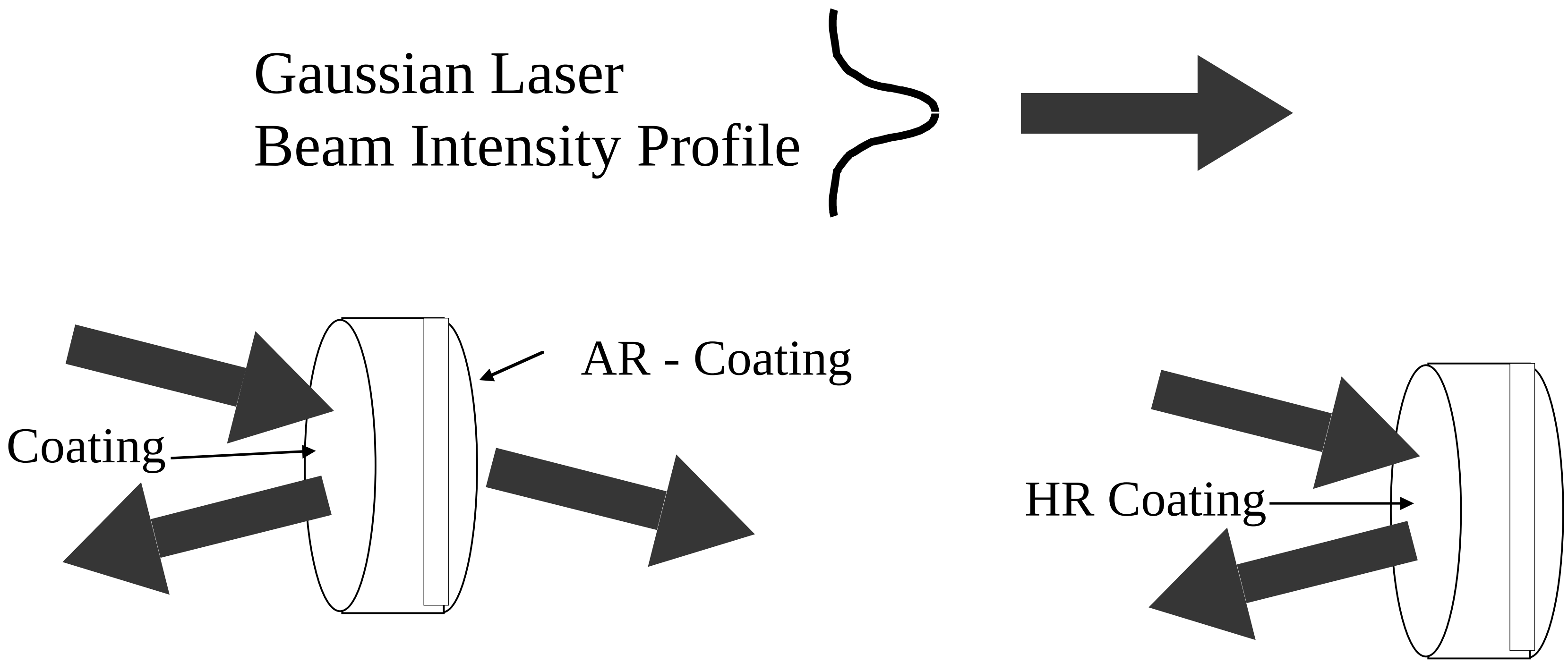
Core Optics Compensation
Zucker (LIGO/MIT)
Thermal Modeling - Beausoleil (Stanford)

Core Optics - Sapphire Growth, Figure, Polish, Absorption and Coatings
Camp (LIGO/Caltech), Billingsley (LIGO/Caltech)
Fejer (Stanford)

Optical Materials Map of LIGO II



Nonuniform Heating

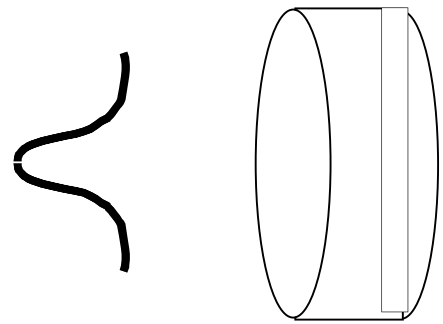


Absorption in Coating,
Substrate and AR - Coating

Absorption
HR Coating

Optical Distortions

Nonuniform
Temperature
Profile



Thermo-Optic Distortions
Produce Thermal Lensing

dn/dT and dL/dT

Thermo-Elastic Deformations
Lead to Figure Errors

dL/dT

Interferometer Power Handling Model

Modal Model includes

Absorption in substrates and coatings

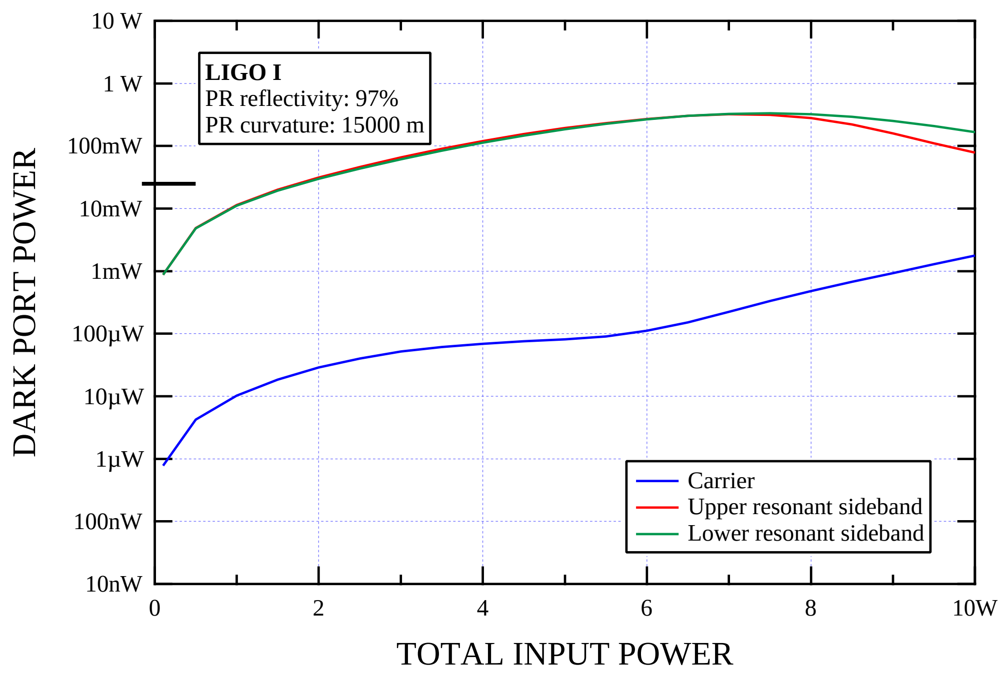
Thermal-optic lensing of beamsplitter, recycling and arm input mirrors

Thermo-elastic deformations of all arm mirrors

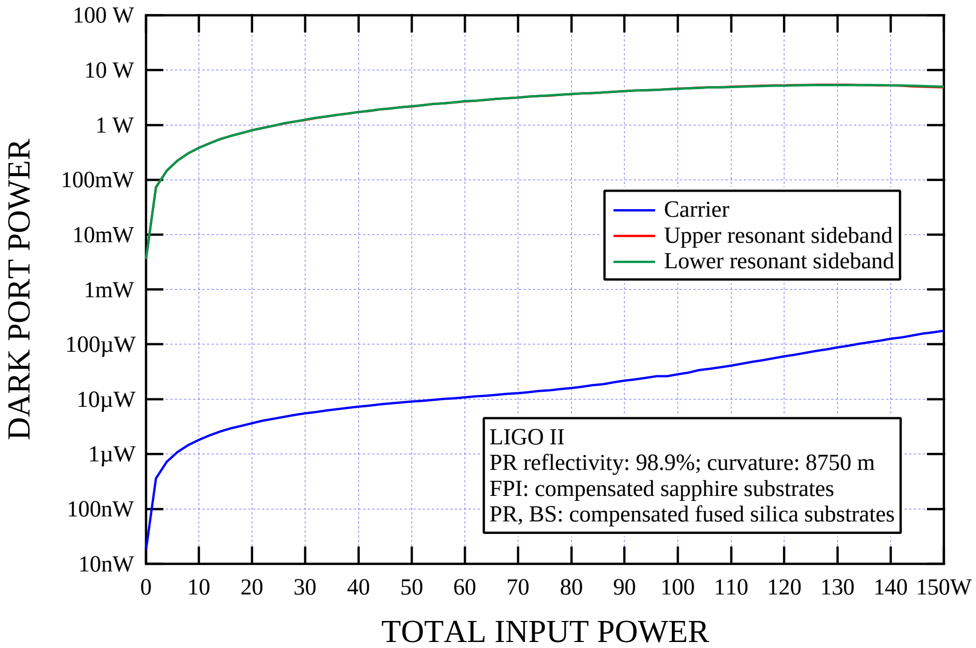
Full set of sidebands

Computes power in carrier and sidebands and all ports

LIGO I Dark Port Output Power



LIGO II Dark Port Output Power



Stabilized Laser Requirements

LIGO I

Wavelength = 1064 nm
Power = 6 watts TEM_{00}

dI/I $=10^{-7}/\sqrt{Hz}$ @ 100 Hz
dI/I $=10^{-10}/\sqrt{Hz}$ @ mod. freq.

Frequency Noise
$S_f(f) = 10^{-7}$ Hz/$\sqrt{Hz}$ @ 150 Hz

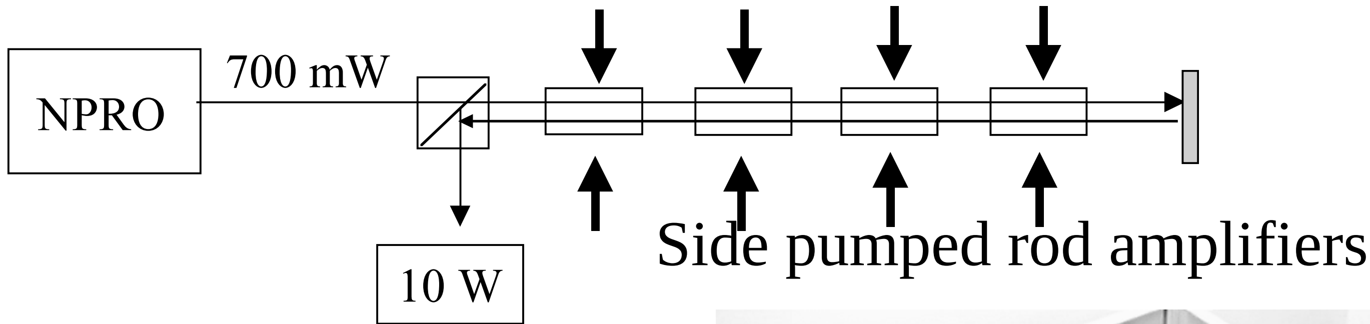
LIGO II

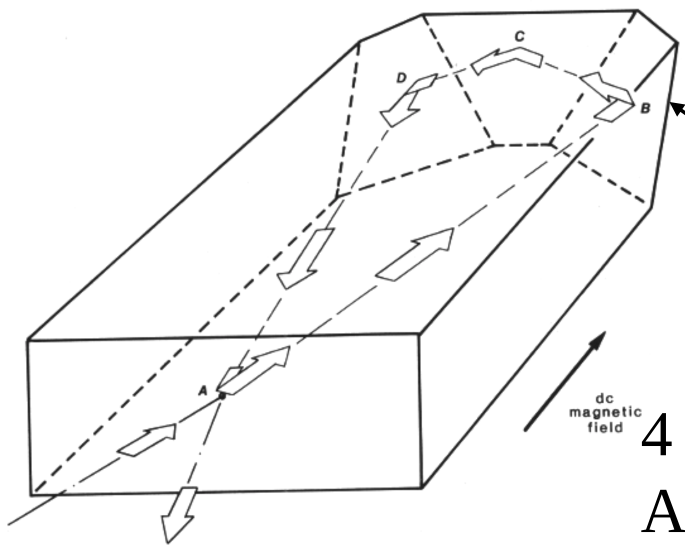
Wavelength = 1064 nm
Power = 120 watts TEM_{00}

dI/I $=10^{-8}/\sqrt{Hz}$ @ 100 Hz.
dI/I $=10^{-11}/\sqrt{Hz}$ @ mod. freq.

Frequency Noise
$S_f(f) = 10^{-8}$ Hz/$\sqrt{Hz}$ @ 150 Hz

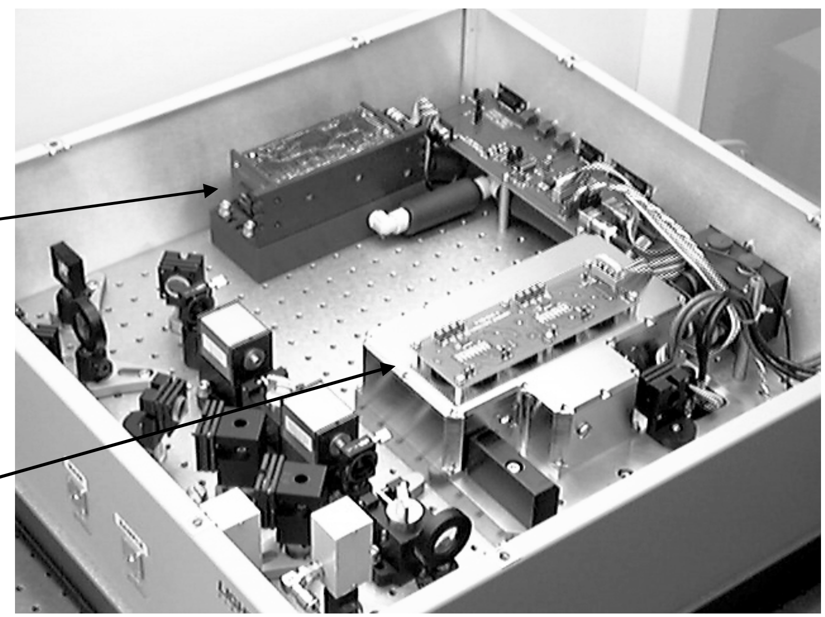
LIGO I Laser Master Oscillator Power Amplifier





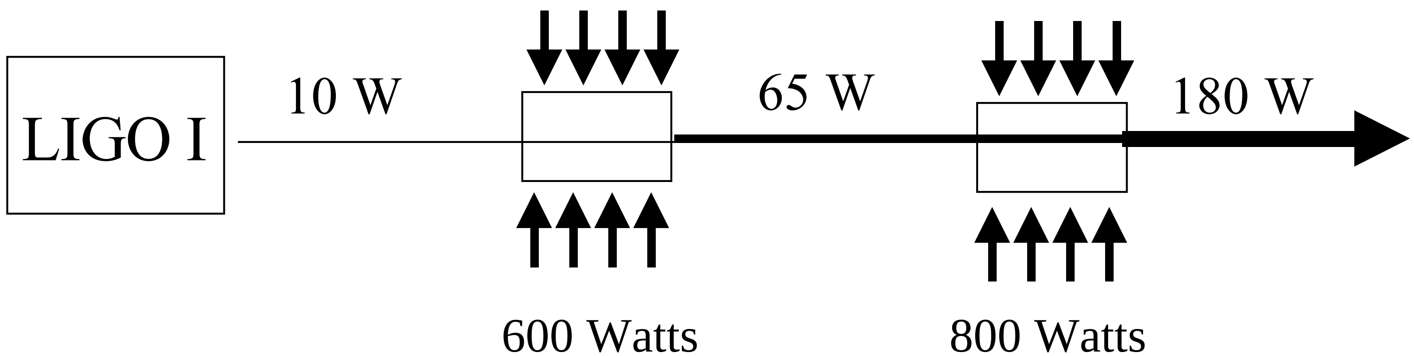
NPRO

4 Stage Amplifier



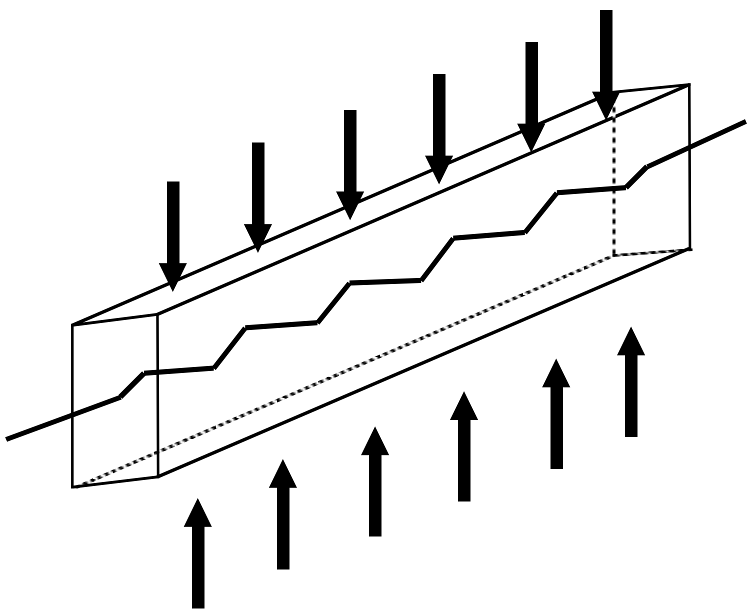
LIGO II Laser

LIGO I Laser is the Master Oscillator for LIGO II Laser



Edge Pumped Zig-Zag Slab Amplifiers

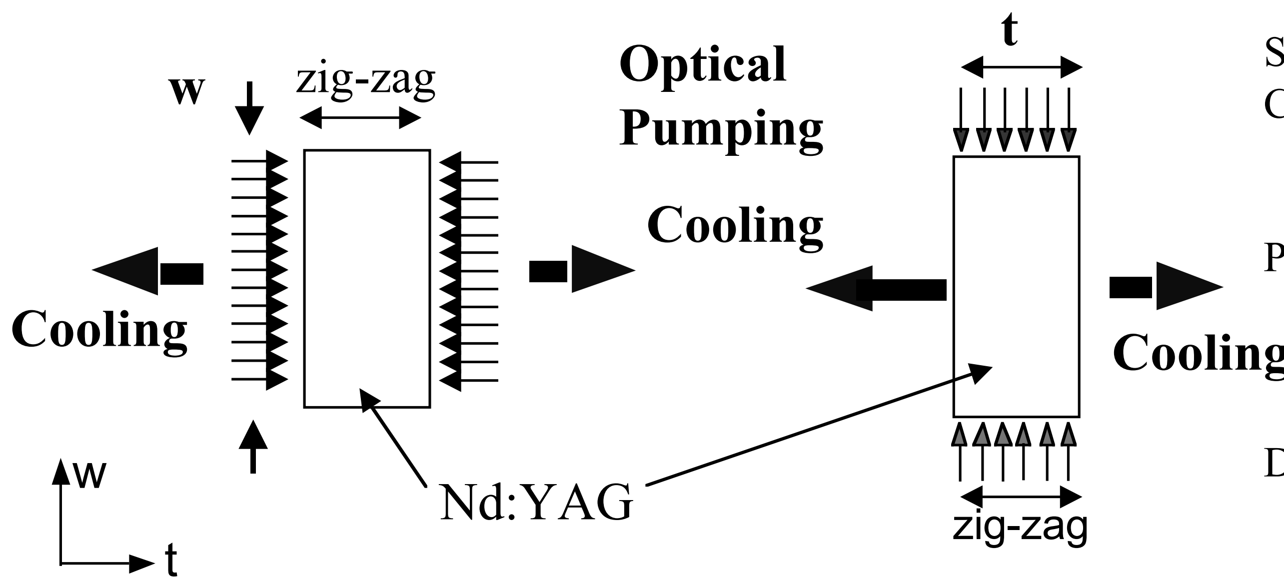
Slab Laser Design



- Uniform pumping→ uniform heating
- Cooling→ 1-D thermal gradient
- Zig-zag path→ no first order thermal lens
- No first order spatially dependent birefringence

Average power scales with area of cooled surface without loss of beam quality

Edge Pumped Slab Amplifier



- Separate pumping and cooling faces
- 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

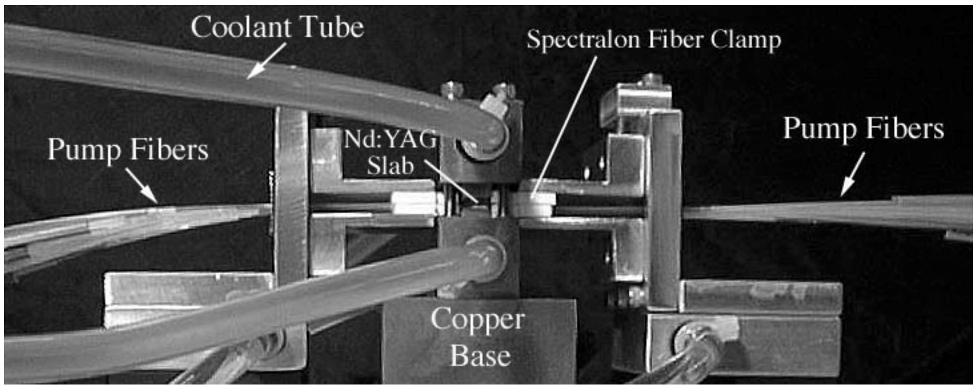
Edge - Pumped

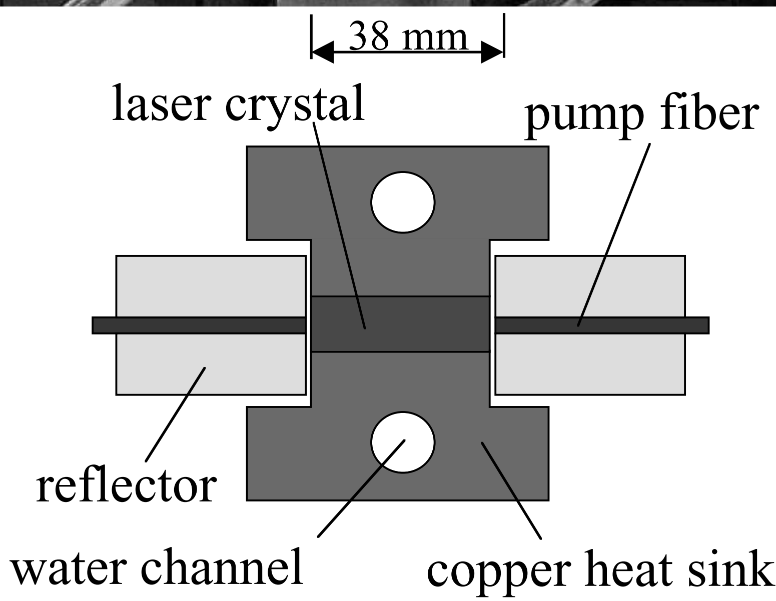
Cooling face ≠ Pumping Face

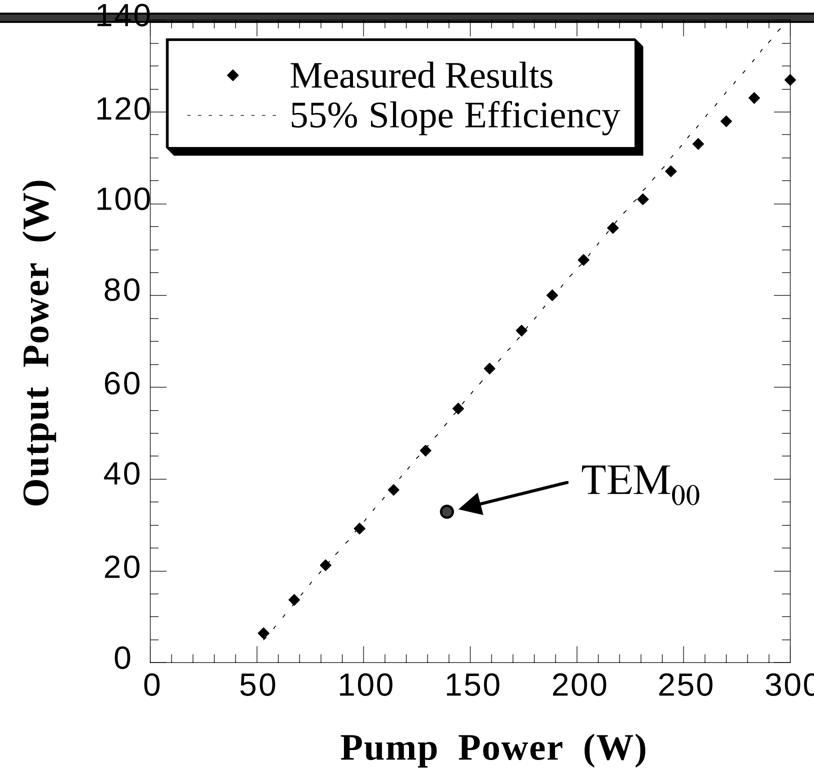
Stress fracture (w/ t)

Pump Absorption w

Thermal Engineering Issues

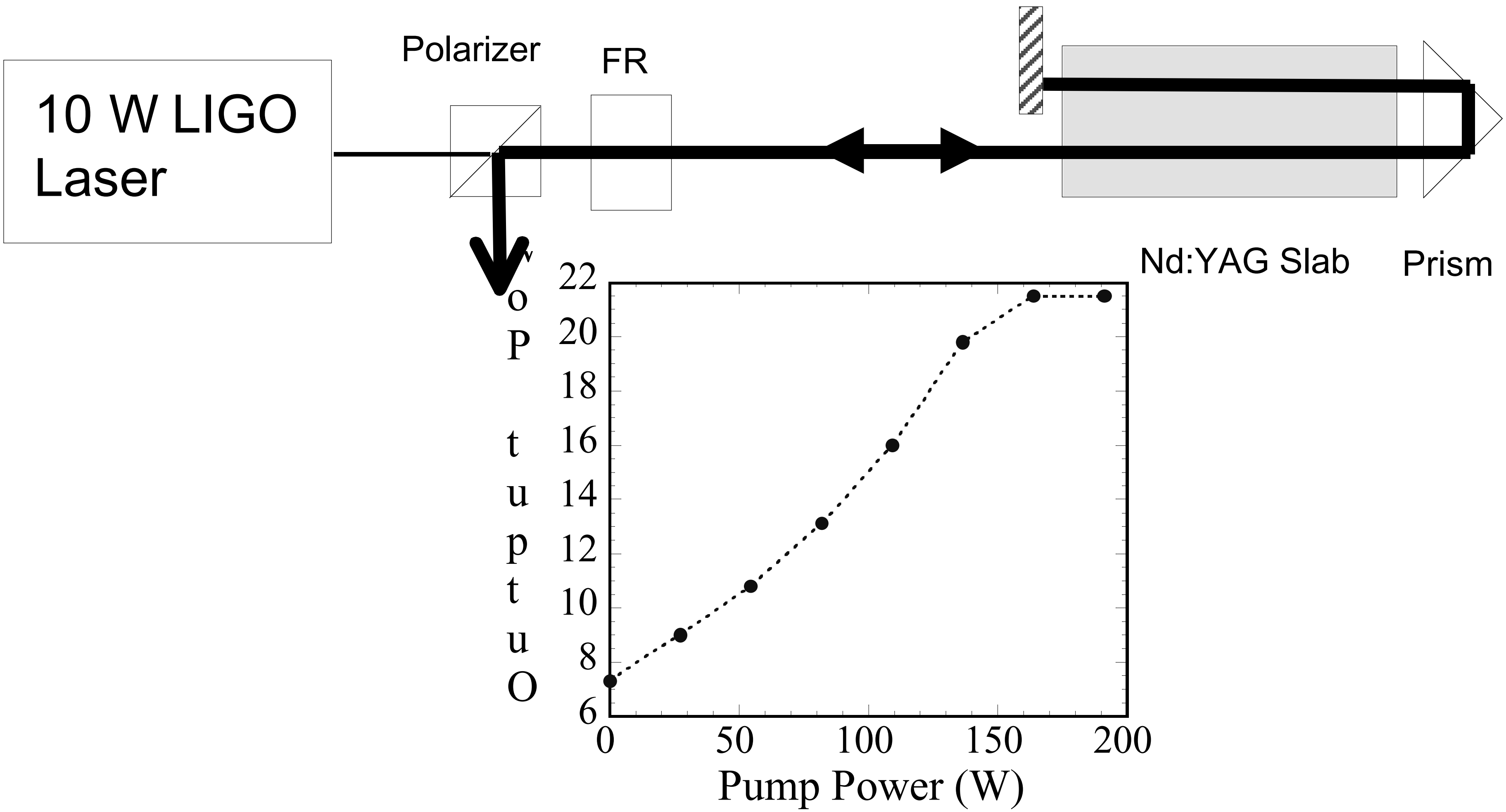




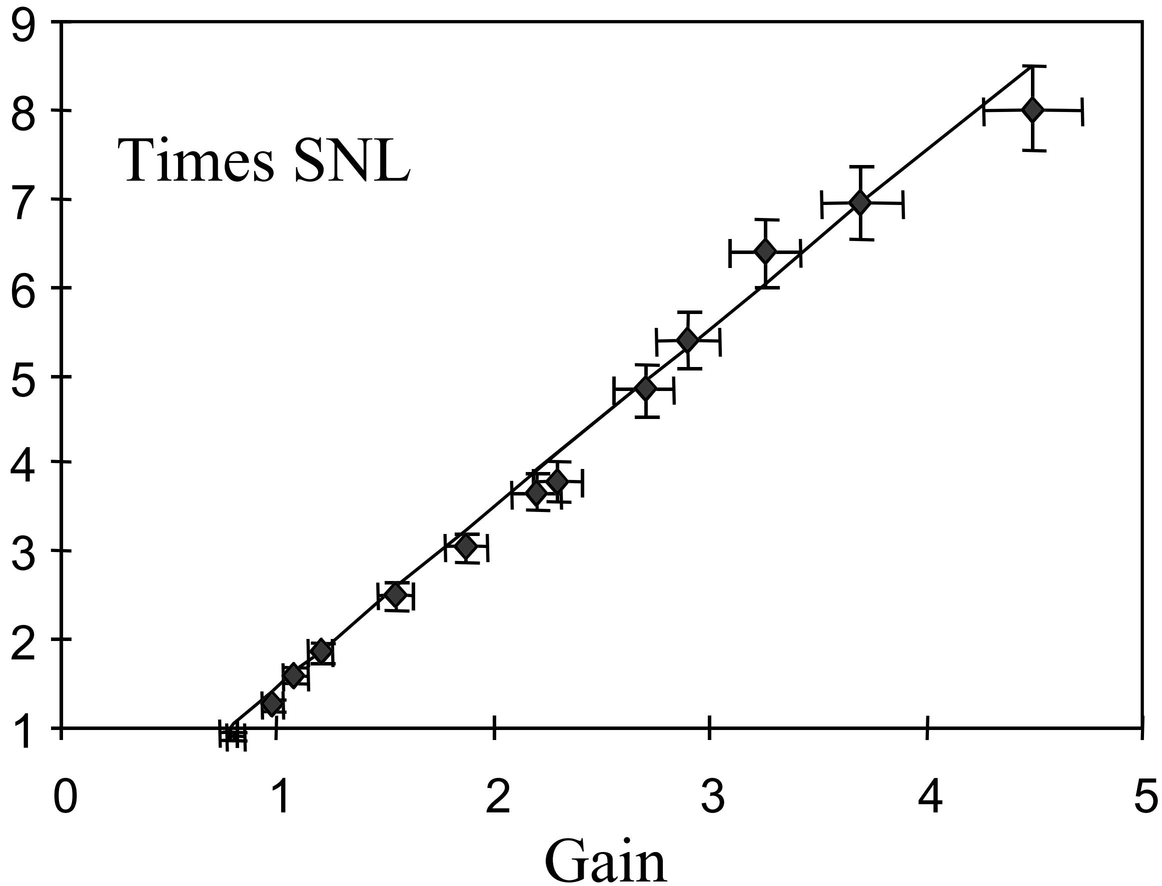


- 55% Slope Efficiency
- 42% Optical-Optical Efficiency
- 90% Pump Absorption Efficiency

Multipass Amplifier



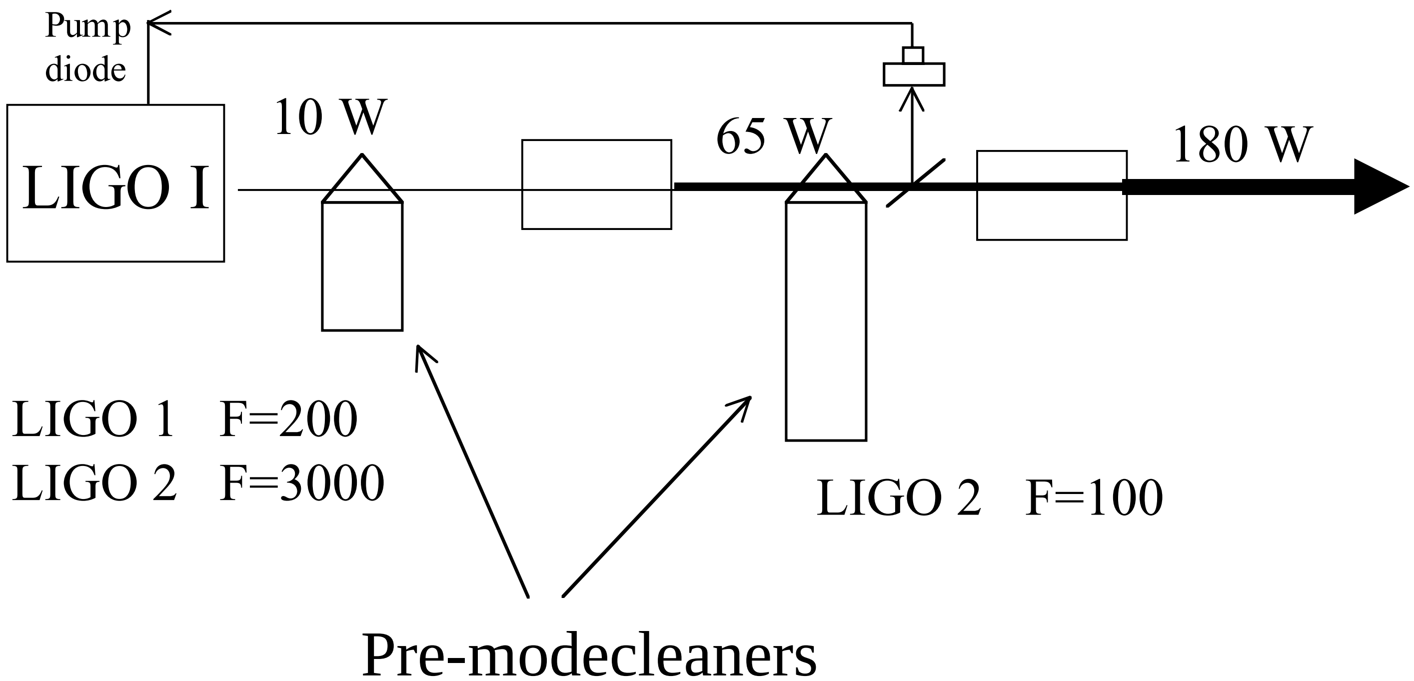
Amplifier Noise



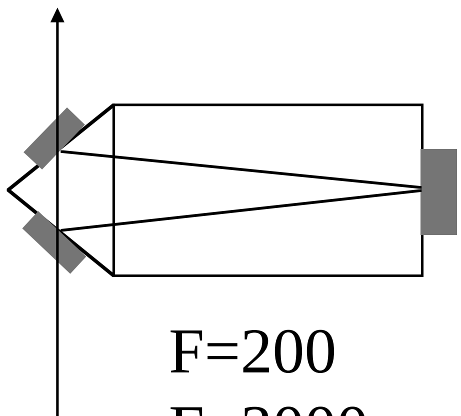
$$\frac{\sigma^2}{\sigma^2_{Shot}} = 1 + 2\,\eta\,\eta_{sp}\,(G-1)$$

Pre-Stabilized LIGO Laser

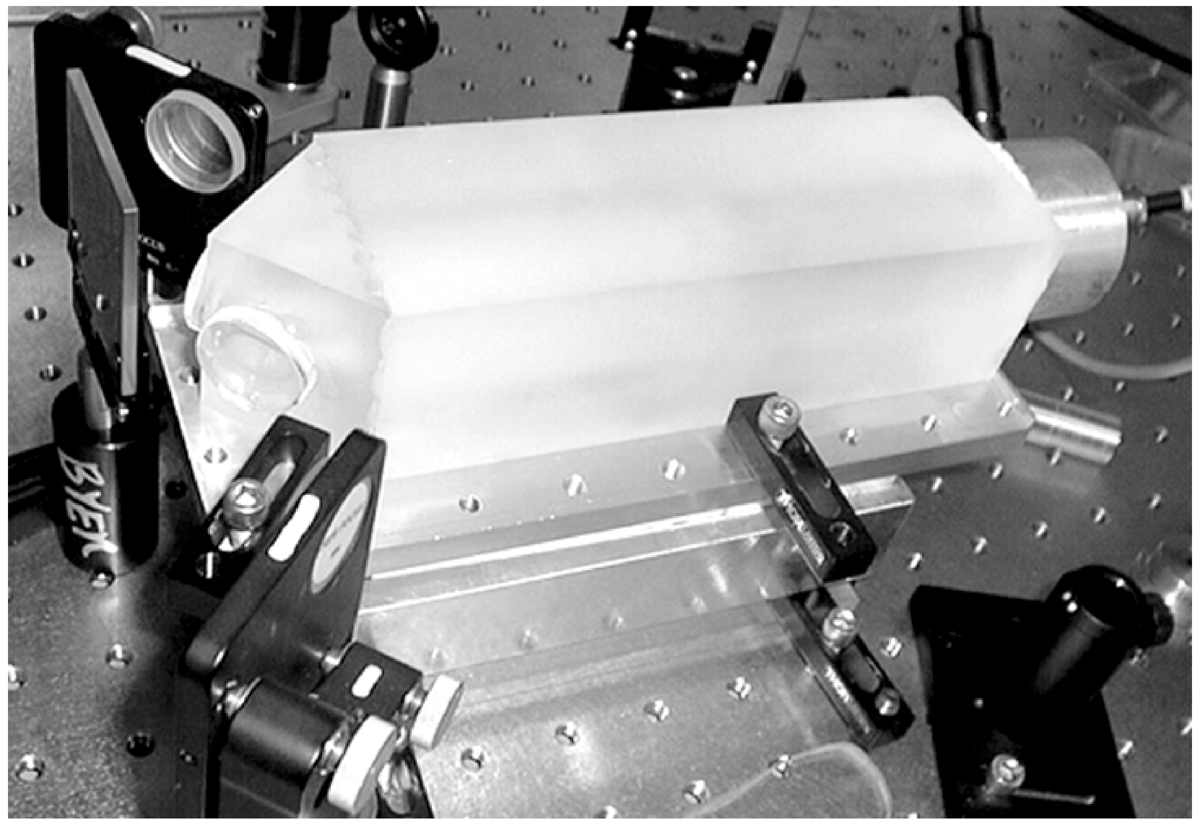
Largely Unchanged from LIGO I



Pre-Modecleaner



F=200
F=3000



Core Optics and Mirror Coatings

<u>Substrate</u>
a-axis Sapphire

28 cm diameter
12 cm thick
30 kg

Q = $3x10^8$

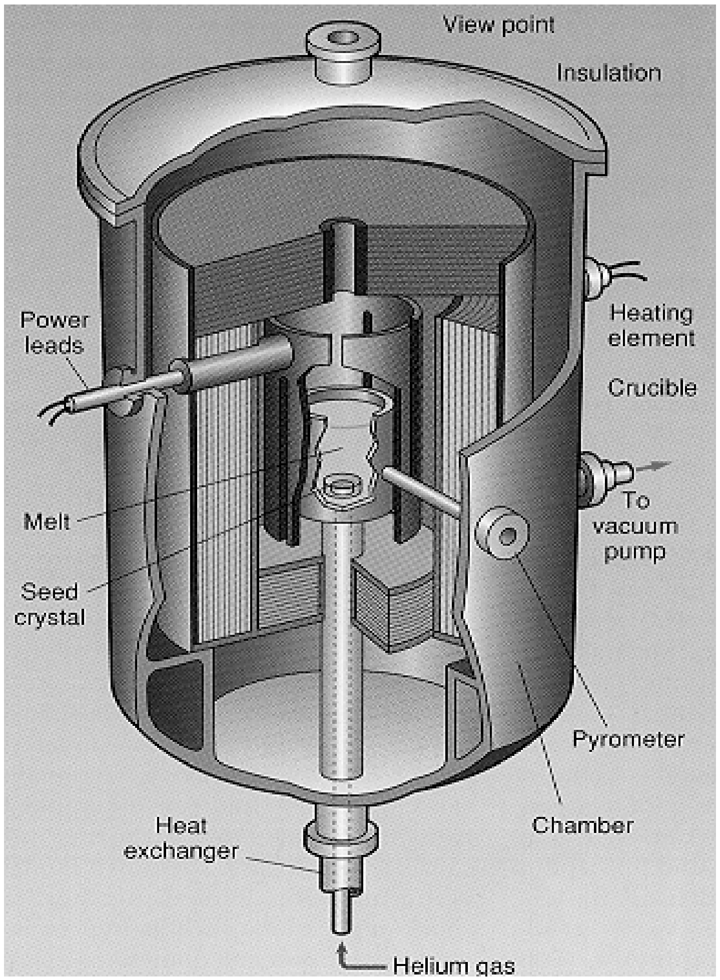
<u>Substrate</u>
Absorption < 40 ppm/cm
"Homogenity" < 40 nm p-v

Figure < 1.0 nm rms
Polish < 0.25 nm rms
ROC ~10 km

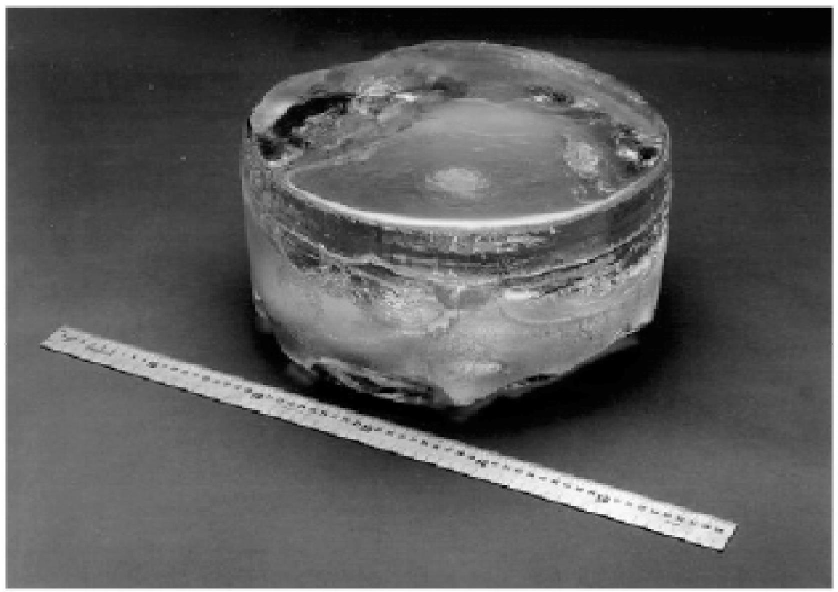
<u>Optical Coating</u>
Absorption < 1 ppm

Maintains Figure
Maintains Polish
Maintains Q

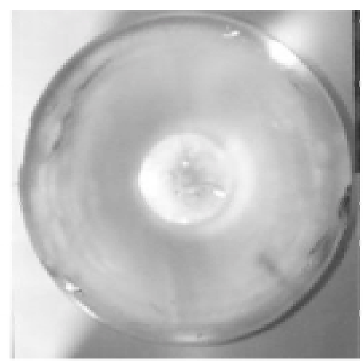
Sapphire Growth by HEM



34 cm Diameter Sapphire Boule



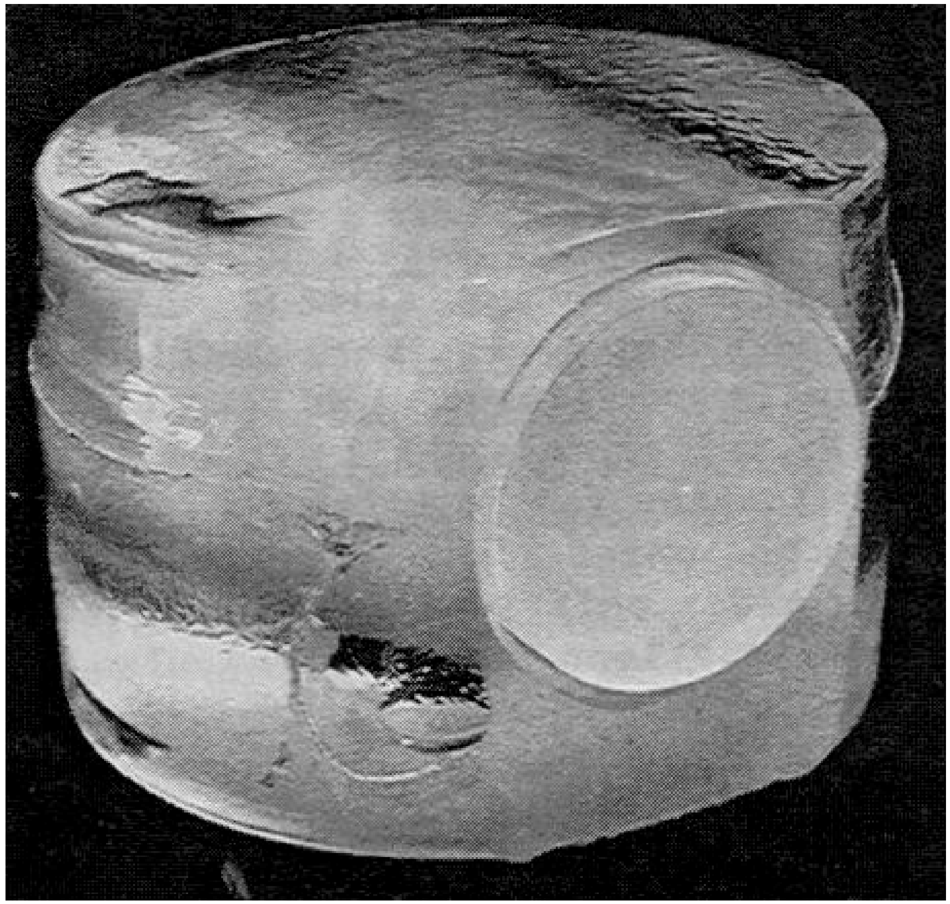
Side



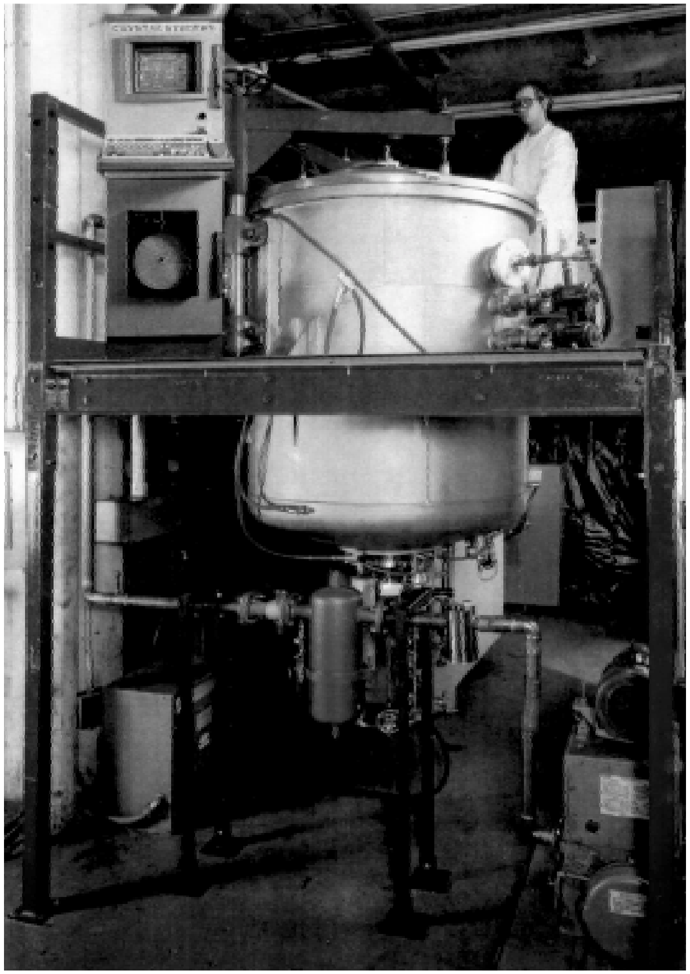
Top

Bottom

C axis Sapphire

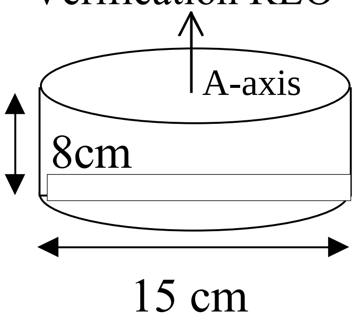


Under Development



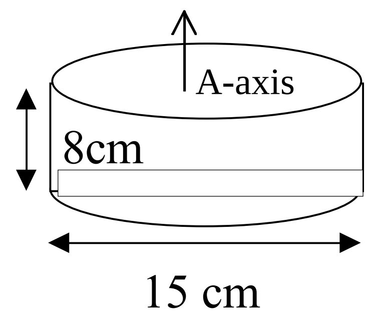
Sapphire Substrate Development Program

Micro Roughness Measurement
General Optics and CSIRO
Verification REO

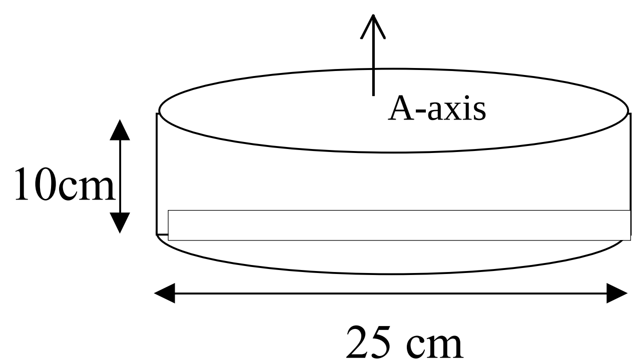


Figuring & Measurement
General Optics and CSIRO
Verification LIGO/Caltech

Transmissive Uniformity
Hughes Danbury 250 nm
1064 nm Fizeau at Caltech

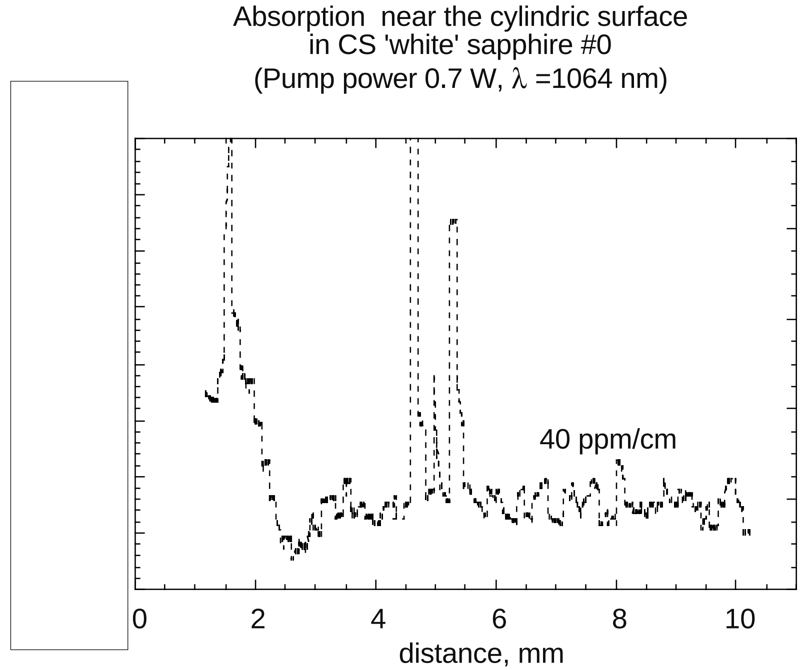


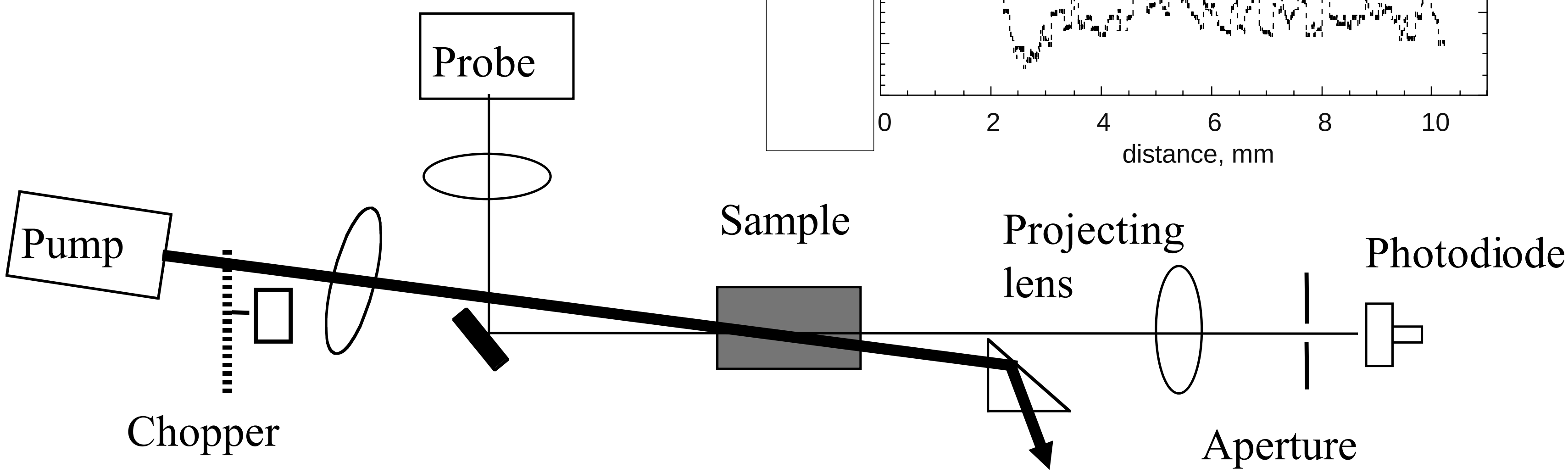
Coating Stress Birefringence
Ellipsometer
Transverse mode splitting



Absorption at 1064 nm in Sapphire

Starting material
Recycled material
Distribution Function - Position
Oxidation State
Annealing
Lattice Quality

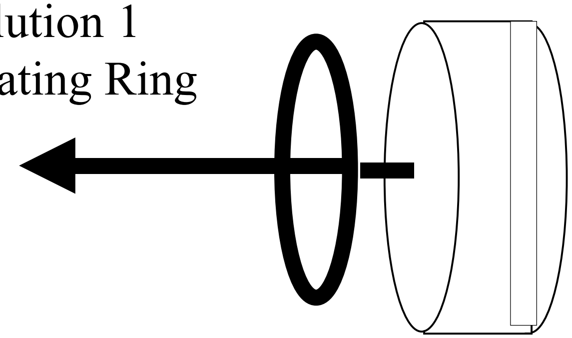




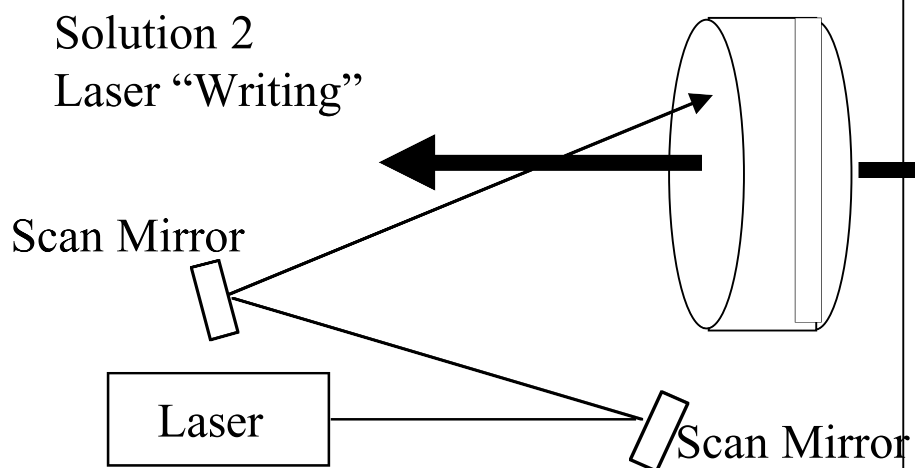
Adaptive Core Optic Control

Reduce by a Factor of 8
the figure error induced
by beam heating

Solution 1
Heating Ring



Solution 2
Laser "Writing"



Work to reduce
the absorption in sapphire
below 40 ppm/cm

Backup

Lower power or injection locked laser

Silica mirrors

Laser writer optical compensation

Several photodiodes

Conclusion

Mode Cleaners & Telescopes

Modulators and Isolators

Photodiodes

Laser and PSL

Core Optics Compensation

Core Optics and Coatings