# Setting the Optical Specs for LIGO

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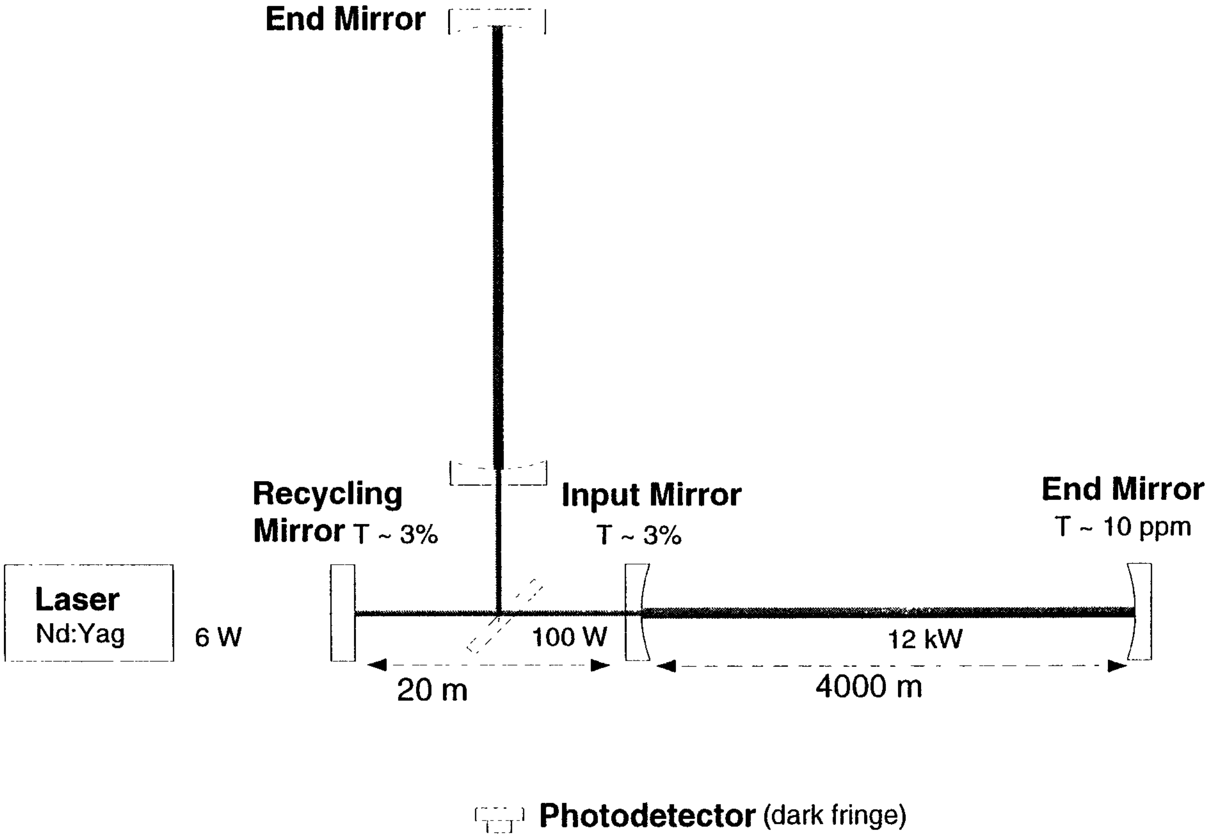
advanced configuration

# Large Optical Components ("Core Optics")

- Test Masses
  - End Mirror
  - Input Mirror
- Beamsplitter
- Recycling Mirror
- Total Number: 20
  - WA 4km: 6 Optics
  - WA 2km: 8 Optics
  - LA 4km: 6 Optics
  - + Spares



# Core Optics Issues

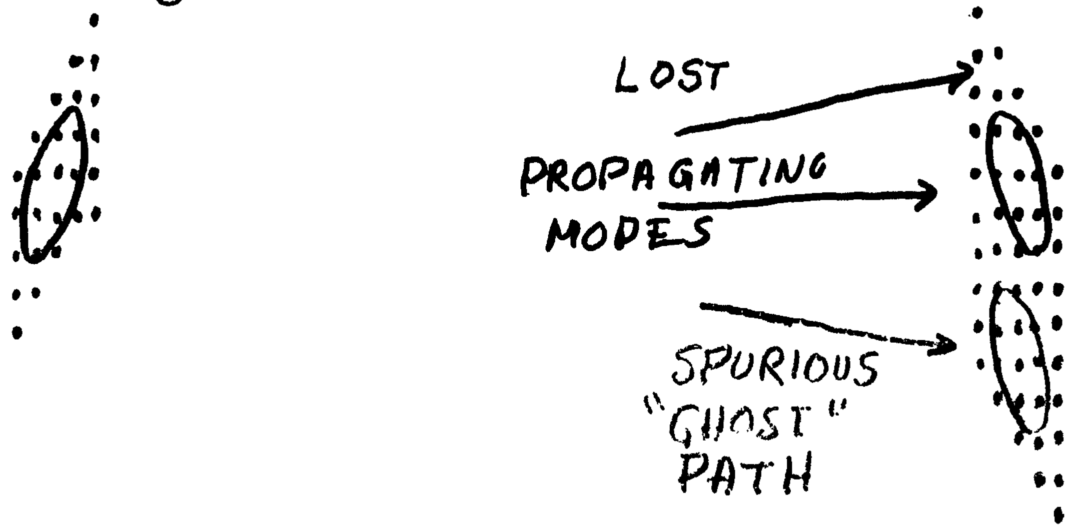
- Optical surface imperfections
  - Radius of curvature: Relative and absolute accuracies
  - Surface figure errors: Low spatial frequency errors leading to small angle scattering
  - Microroughness: High spatial frequency imperfections leading to large angle scatter
- Absorption
  - Coatings
  - Substrates
- Thermal Noise
  - High mechanical Q to minimize thermal noise ($Q \sim 10^6$-$10^8$)
  - Size, density, speed of sound,...

# Evaluating Optics Performance

- Primary tool is computer model of full recycled interferometer
  - ›› FFT-based optical propagation code
  - ›› Includes the surface figure of all optical components (either real or simulated)
  - ›› Includes OPD of substrates
  - ›› Solves for carrier and sidebands for modulation/demodulation
- Contributions from many people
  - ›› Original code courtesy of Jean-Yves Vinet and Patrice Hello (VIRGO)
  - ›› Extensive modification and enhancement by Partha Saha, Yaron Hefetz, and Brett Bochner
  - ›› Used to establish initial LIGO requirements by Bill Kells

# FFT Interferometer Model

- Most studies performed with 35 cm x 35 cm window covered by 128 x 128 grid



- Realistic accounting of of small angle scatter out to

$$\theta \approx \lambda/(\Delta x) \approx 0.4\,\mathrm{mrad}$$

- Larger angle scatter taken into account with overall loss term

# Initial Core Optics Requirements

- Tight matching of all optical parameters arm to arm

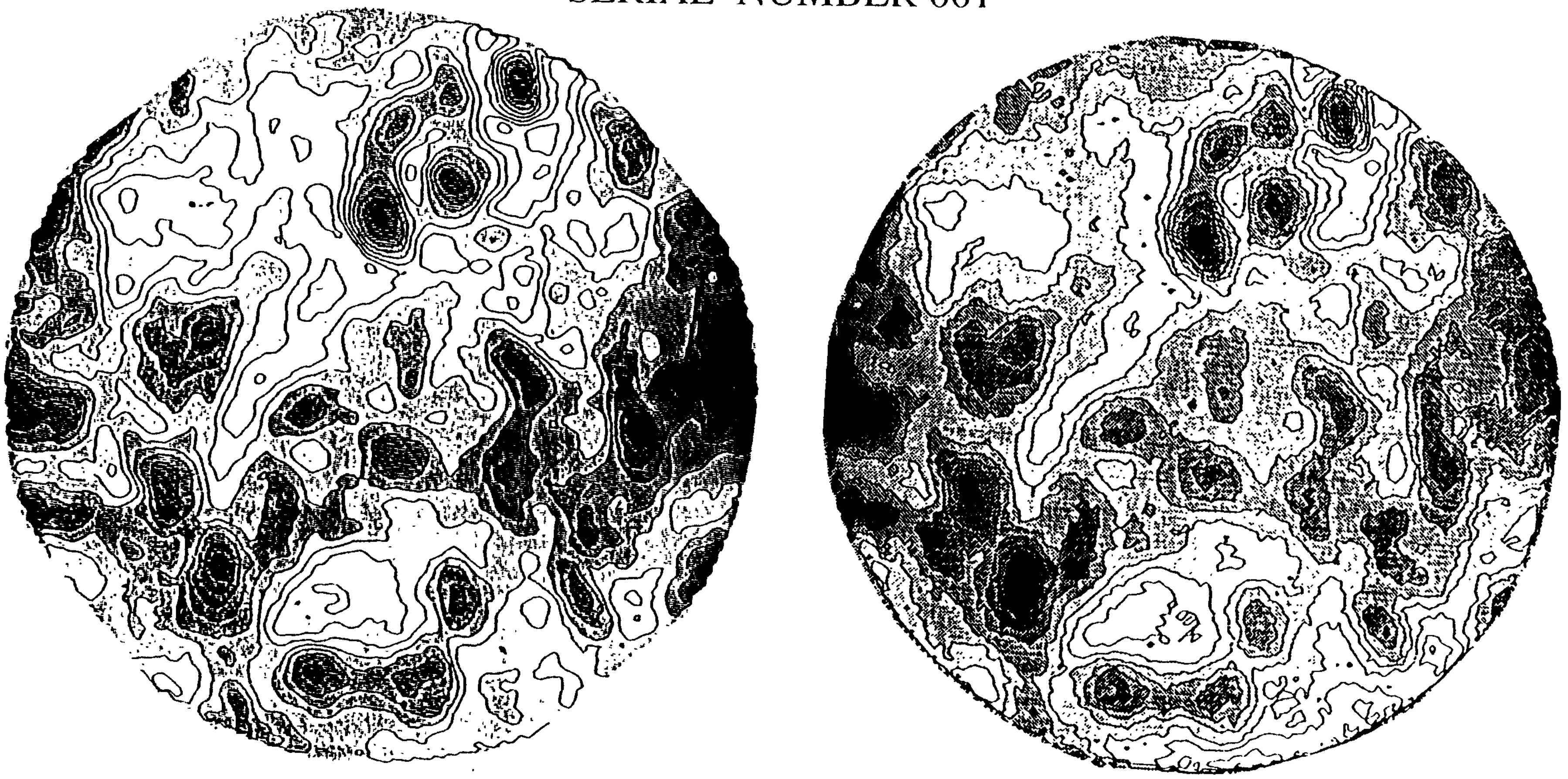
| ***Physical Quantity*** | ***Test Mass*** | | ***Beam splitter*** | ***Recycling mirror*** |
|---|---|---|---|---|
| | ***End*** | ***Input*** | | |
| **Diameter of substrate, $\phi_s$ (cm)** | **25** | **25** | **25** | **25** |
| **Substrate Thickness, $d_s$ (cm)** | **10** | **10** | **4** | **10** |
| **1 ppm intensity contour diameter (cm)** | **24** | **19.1** | **30.2**[a] | **19.2** |
| **Lowest internal mode frequency (kHz)** | **6.79** | **6.79** | **3.58** | **6.79** |
| **Mass of Suspended Component (kg)** | **10.7** | **10.7** | **6.2** | **10.7** |
| **Nominal surface 1 radius of curvature (m) and $g_i$ factor** | **7400**<br>$g_2$**=.46** | **14540**<br>$g_1$**=.725** | $\infty$ | **9890**<br>**g=.9984** |
| **Tolerance on radius of curvature (m)** | **absolute: +220**<br>**matching: ±111** | **-1000, +145** | **>-720 km convex,**<br>**>200 km concave** | **-100, +500** |

a. For these 45° angle of incidence optics, this is the smallest diameter circle centered on the optic face which is everywhere outside of the 1 ppm intensity field.

# Core Optics-Polishing

- Conclusion: rms deviation from sphere < 1nm over 20cm diameter are achievable!
  - ›› In some cases, apparent rms ~0.5 nm measured
- With care, measurements at ≤ 1 nm level possible
  - ›› Reproducible features seen; Consistent intercomparisons demonstrated
  - ›› Small, subtle systematic effects noticed
    - — **Flat reference vs. curved surface**
    - — **Fizeau path differences**
    - — **Focus effects**

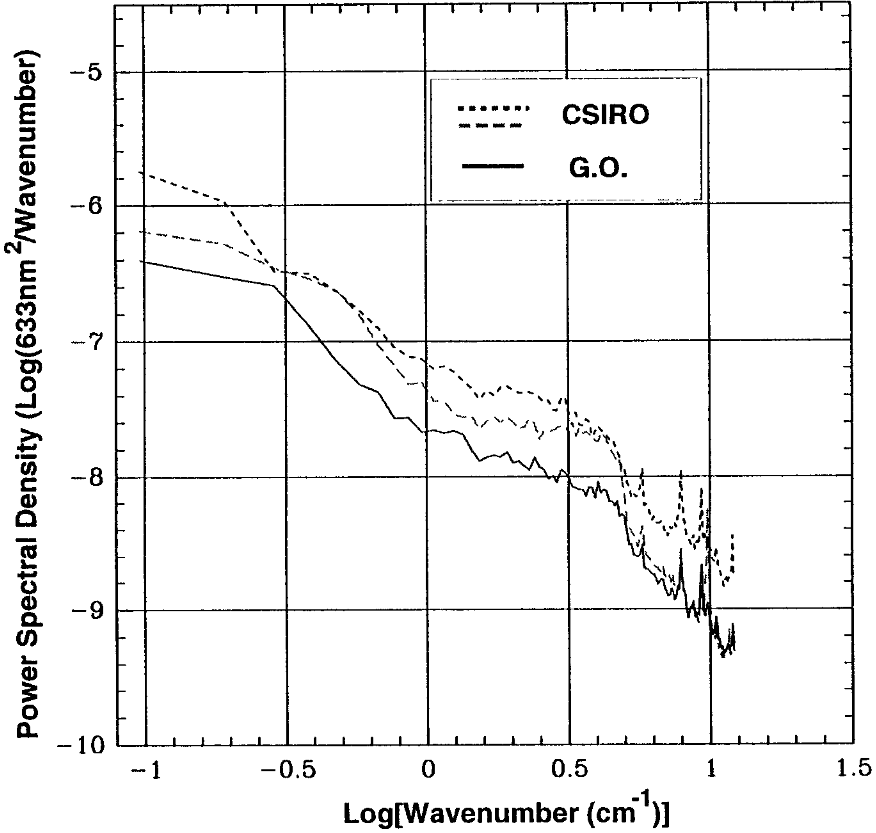
# CONTOUR INTERVAL ~ 1 NANOMETER
SERIAL NUMBER 001



HDOS MEASUREMENT
(1.58 nm RMS)

NIST MEASUREMENT
(1.75 nm RMS)

# Surface Figure Errors



- NIST Measurements

↑ Limit of FFT Simulation

# Microroughness/Large Angle Scatter

- Largest source of lost optical power in initial detectors
- Industry definition of microroughness is typically tied to measurement instrument
  - LIGO "definition" includes spatial frequencies 4.3-7500 $\mathrm{cm}^{-1}$
- For simple "smooth" surfaces,

$$\text{Scatter Loss} = \left(4\pi\frac{\sigma}{\lambda}\right)^2$$

  - For $\lambda = 1.063\mu\mathrm{m}$, $\sigma = 0.2\mathrm{nm}$, scatter loss ~ 6 ppm
- Point defects cause few ppb loss each
- Conventional wisdom says that substrate roughness dominates over coating nonuniformity at high spatial frequencies

# Pathfinder Microroughness Results

- Comparative surface roughness measurements made at REO

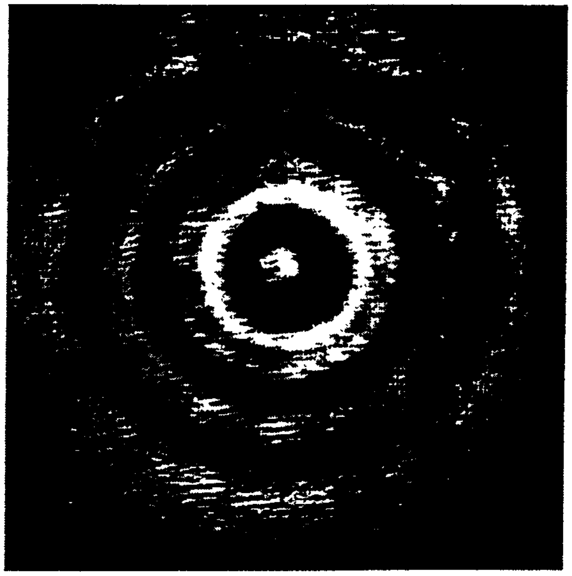
| Polisher | Optic/Surface | Microroughness (Å rms) | |
|---|---|---|---|
| | | **Micromap SW (5 location ave.)** | **PSD area analysis (R. Weiss)** |
| CSIRO | 006/Curved | 3.6 | 3.7 |
| | 006/Flat | 2.8 | 2.7 |
| GO | 005/Curved | 0.85 | 0.6 - 1.4 |
| | 005/Flat | 0.88 | 0.7 - 1.2 |

- CSIRO microroughness improved to 1-2 Å in initial LIGO production

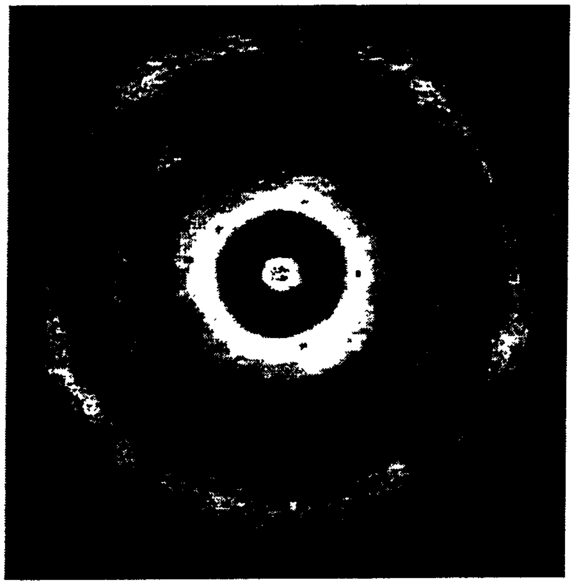
# Coating Uniformity Development

- Coating Uniformity Development: REO
  - Goal: Scale up low loss ion beam sputtered coating technology to LIGO diameters
  - Preliminary test pieces show good uniformity to 15 cm diameter
  - Final verification: Coat Pathfinder optics for 633 nm and test
- Development of new test technique
  - Measurements: Doug Jungwirth, Alex Golovitser
  - Analysis: Hiro Yamamoto, Bill Kells
  - Coatings: Research Electro Optics, Ramin Lalezari, Dale Ness
- Conclusion: Large-scale uniformity at 0.5 nm level is possible with current technology

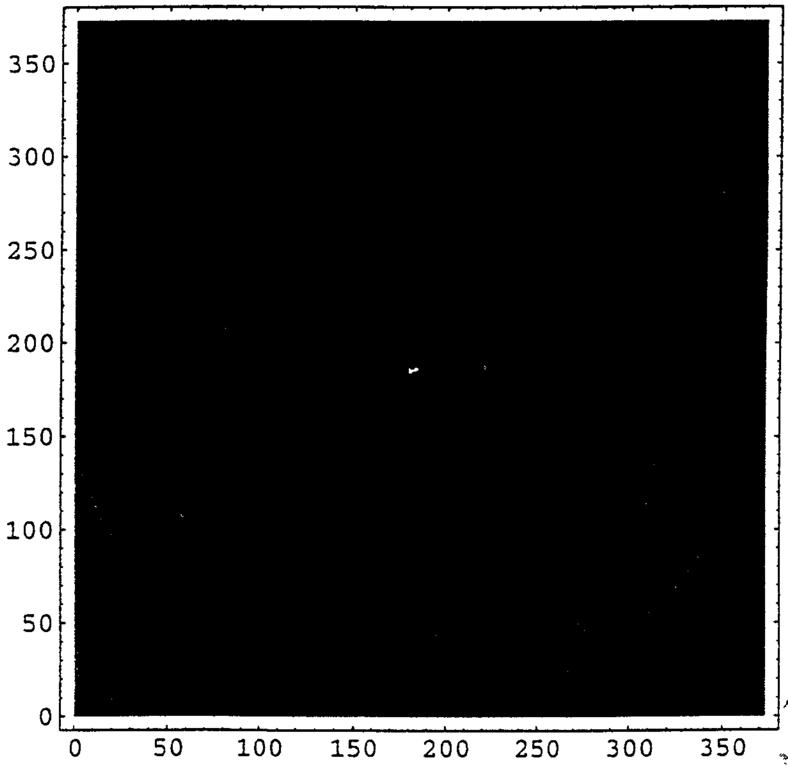
Uncoated



Coated



Difference



~0.6 nm
(RMS)

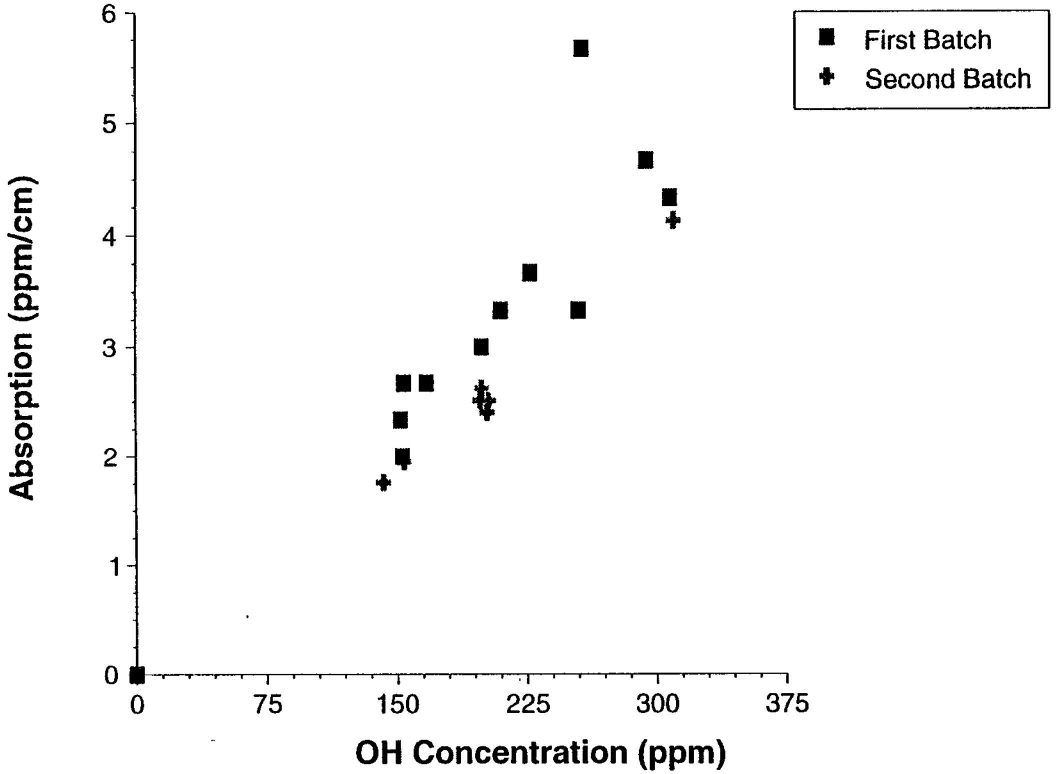
# Absorption Effects

- Surface distortion
  - Important for reflective and transmissive optics
  - Typically not important in $SiO_2$ due to low expansion coefficient
- Thermal lensing
  - Important for transmissive optics only
  - Important in $SiO_2$ due to low thermal conductivity and high dn/dT
- Heat deposition matches beam profile; temperature gradient from heat flow to optic surfaces (radiatively coupled to vacuum chamber)
  - First order distortion is a simple change in radius (or simple lens)
  - Gaussian beam profile leads to higher order distortions

# Absorption Sources

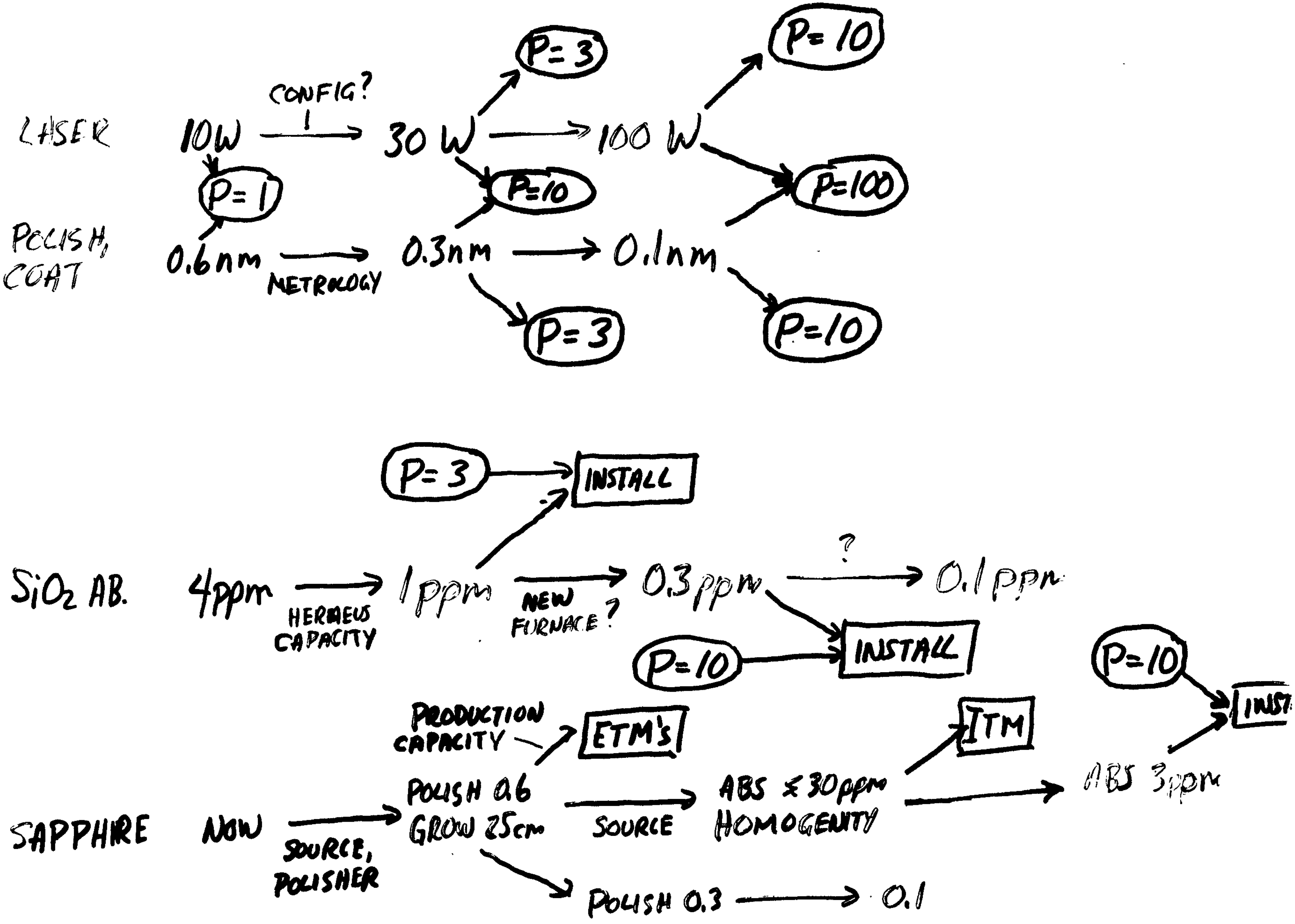
- Coatings
  - ›› Source of absorption unknown
  - ›› IR values (typically?) 0.5 ppm
- Substrates: $SiO_2$
  - ›› IR absorption due to OH (usually?)
    - **Typically 2-20 ppm/cm**
  - ›› Shorter wavelength absorption due to metallic impurities (?)
    - **Typical value at 514 nm ~ 2 ppm/cm (?)**
- Substrates: Sapphire
  - ›› Source of absorption unknown
  - ›› IR values range from 3-1000 ppm/cm

# Absorption in $SiO_2$



# Future Directions

- Polishing
  - Surface figure improvements (factor 5?)
- Coatings
  - Higher uniformity, lower absorption (factor 10?)
- $SiO_2$ substrates
  - Understand limits to Q (fundamental limit or technical limit)
  - Reduced OH concentration (factor 10?)
  - Larger sizes
- Sapphire substrates
  - High Q, high density, high speed of sound desirable for thermal noise
  - High thermal conductivity good for thermal lensing
  - Problems: optical figure, birefringence, homogeneity, absorption,....


LASER
10W
CONFIG?
30 W
100 W
P=3
P=10
P=1
P=10
P=100
POLISH, COAT
0.6nm
METROLOGY
0.3nm
0.1nm
P=3
P=10
P=3
INSTALL
SiO2 AB.
4ppm
HERAEUS CAPACITY
1ppm
NEW FURNACE?
0.3ppm
?
0.1ppm
P=10
INSTALL
P=10
INST
PRODUCTION CAPACITY
ETM's
ITM
SAPPHIRE
NOW
SOURCE, POLISHER
POLISH 0.6
GROW 25cm
SOURCE
ABS ≤ 30ppm
HOMOGENITY
ABS 3ppm
POLISH 0.3
0.1

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