JCC

# The LIGO Pre-stabilized Laser


Rick Savage
LIGO Hanford Observatory


Sept. 2, 1997


R. Abbott
A. Abramovici
L. Cardenas
P. Fritschel (MIT)
E. Gustafson (Stanford).
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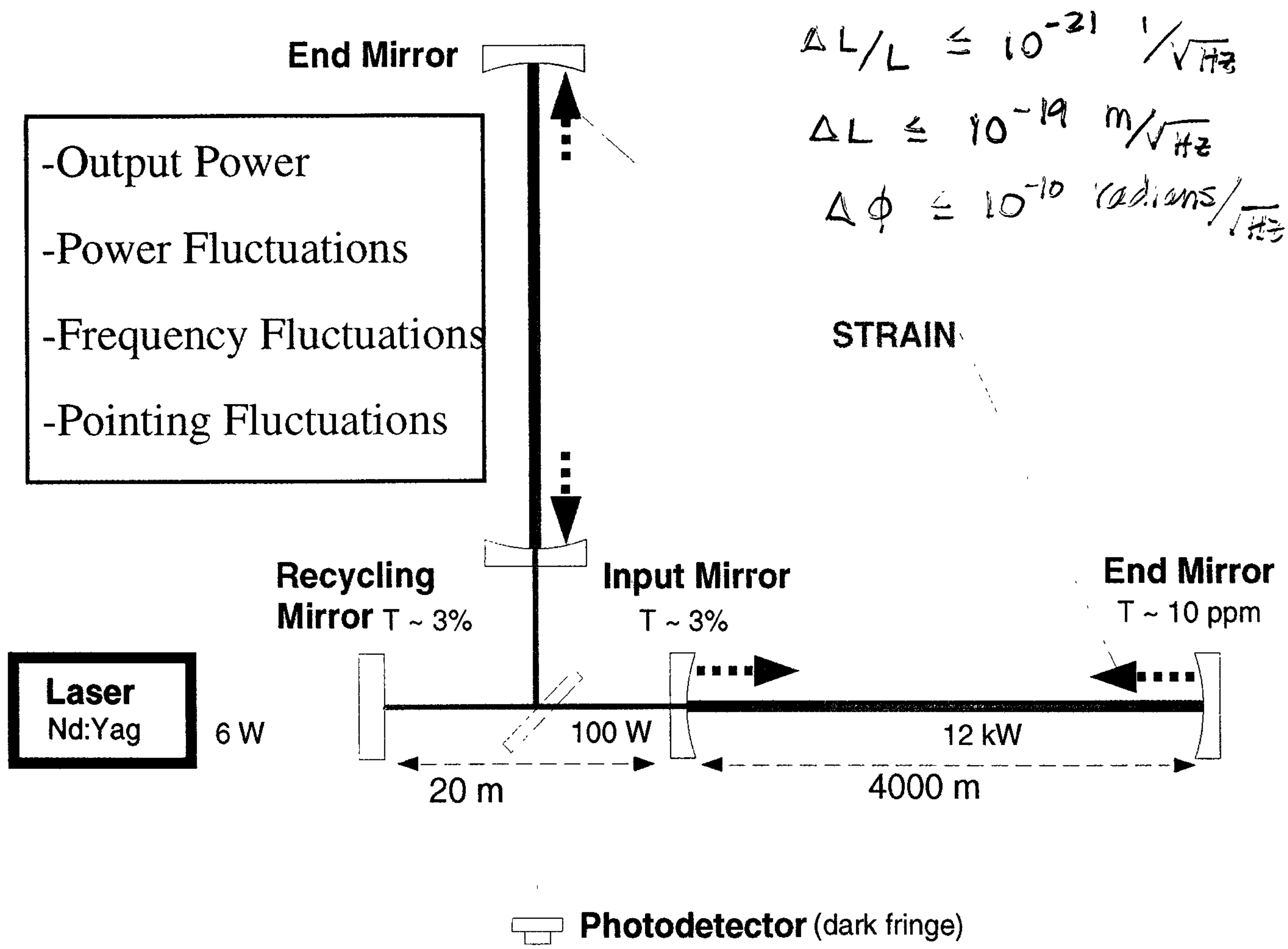
LIGO Caltech Science Meeting

LIGO-G970222-00-D

# Using the Laser Radiation as the Yardstick



# Power Fluctuations In the Grav. Wave Band.

$V = A\,x$

$A \propto P = C \cdot P$

$V = C \cdot P \cdot x$

$V \equiv$ gravity output signal

$A \equiv$ discriminator transfer function in V/m

$x$ = offset from resonant length diff.

$C$ = constant

$$\frac{dV}{dt} = C\left[\frac{dP}{dt}\cdot x + P\cdot\frac{dx}{dt}\right]$$

GW noise due to power noise coupling via offset from resonance

Desired GW signal

require $\frac{dP}{dt}\cdot x \le \frac{1}{10}\,P\cdot\frac{dx}{dt}$

$$\frac{dP}{P} \le 0.1\,\frac{dx}{x}$$

$dx \sim 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz

$x \simeq 10^{-13}$ m (nominal rms cavity offset).

$$\frac{dP}{P} \text{ or } \frac{dI}{I} \le 0.1\,\frac{10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}}{10^{-13}\,\mathrm{m}} = \underline{\underline{10^{-7}\ 1/\sqrt{\mathrm{Hz}}}}$$

# Beam Pointing Fluctuations

relative angle fluctuations

relative disp. fluct.

* $$\delta L_{-} \simeq 7.1\cdot 10^{-21}\left(\frac{\psi_z}{10^{-8}\,\text{rad}}\right)\left(\frac{\sqrt{\alpha^2+(0.16x)^2}}{4\cdot 10^{-9}/\sqrt{\text{Hz}}}\right)\ \frac{\text{m}}{\sqrt{\text{Hz}}}$$

SRD Requirement (1.005 rule)

static alignment offset

$$\sqrt{\alpha^2+(0.16x)^2} \leq 4\cdot 10^{-9}/\sqrt{\text{Hz}}.$$

assume two terms contribute equally.

$$(2\alpha^2)^{1/2} \leq 4\cdot 10^{-9}/\sqrt{\text{Hz}} \qquad \alpha \leq 2.8\cdot 10^{-9}.$$

$$2\,(0.16x)^2 \leq 4\cdot 10^{-9}/\sqrt{\text{Hz}} \qquad x \leq 1.8\cdot 10^{-8}$$

$$\alpha = \delta\theta/\Theta_{d/2} \leq 3\cdot 10^{-9}.$$

$$x = \frac{\delta x}{w_0}$$

** 12-m mode cleaner filtering of 1st higher order mode
$\times\ .0014$

$$\longrightarrow \delta\theta/\Theta_{d/2} \leq 2.0\cdot 10^{-6} \qquad \frac{\delta x}{w_0} \leq 1.3\cdot 10^{-5}$$

* ASC DRD Appendix 5

** IOO CDD p.13.

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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| Document Type | LIGO-T950047-01 - | E | 8/4/95 |
|---|---|---|---|

# Evaluation of Nd:YAG(1064nm) Lasers for Use in the Initial LIGO Interferometers

A. Abramovici, D. H. Shoemaker

This is an internal working note
of the LIGO Project..

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# 2 SUMMARY OF TECHNICAL MERITS

Nd:YAG is expected to be a light source which will be suitable for enhanced and advanced LIGO interferometers. In the laboratory, Nd:YAG and other solid-state lasers exist already which are suitable for engineering into 'enhanced' interferometers (with 40 W of power, equivalent to 20 W of Argon 514 nm light). In contrast, Argon lasers have no promise of more than 20% increases in power. Thus, we see a need to change to solid-state lasers shortly after commissioning of the initial LIGO interferometers.

To first order, then, we wish to anticipate that change and to test if we cannot start the initial LIGO interferometers with a light source and wavelength which would allow an adiabatic change to higher power. This can save schedule, and reduce the net cost, of arriving at an enhanced level of shot-noise limited sensitivity.

A second reason to investigate Nd:YAG lasers at 1064 nm at this time is to evaluate possible performance advantages from the different wavelength. Relaxed mirror specifications, and lower Rayleigh scatter in the substrates, are examples.

In summary, there do not seem to be any aspects of the interferometer performance or engineering difficulty which would be significantly adversely impacted by a change to 1064 nm and Nd:YAG for the initial LIGO interferometers, and all indications that higher power lasers will be in parallel development (driven by a rapidly growing industrial demand). There are a number of places where more in-house effort will be required, to characterize new components, but sharing with laser groups and other GW groups can reduce this burden.

The tables below summarize the differences between a Argon-514nm interferometer and a Nd-YAG-1.06μm laser. Points which can be clearly seen as disadvantages are indicated in *italics*. Details are given in Appendix B. Most categories should be self-explanatory; by 'engineering status' we mean to give a one-line summary of the availability of a commercial solution, the engineering future, the rate of progress in the field, etc.

**Table 3-1: Laser Technical Summary**

| parameter/part | Nd:YAG Merit/*Demerit* | Argon Merit/*Demerit* |
|---|---|---|
| power | initial power available, future power assured; *~2x power required for given sensitivity* | initial power available; *no further increases probable.* |
| efficiency | several $10^{-2}$ | $10^{-4}$ |

| parameter/part | Nd:YAG Merit/*Demerit* | Argon Merit/*Demerit* |
|---|---|---|
| mean time before failure | 10,000 MTBF (commercial specification) 10-20,000 MTBF (Byer experience) | 8000 MTBF (commercial specification) ~2000 MTBF (LIGO experience) |
| failure mode | ~20% reduction in power | *no light* |
| raw frequency noise, 90 Hz | $10^2$ Hz/$\sqrt{\text{Hz}}$ | $10^4$ Hz/$\sqrt{\text{Hz}}$ |
| raw intensity noise, 90 Hz | $10^{-6}$ $\delta I/I$ $1/\sqrt{\text{Hz}}$ | $10^{-4}$ $\delta I/I$ $1/\sqrt{\text{Hz}}$ |
| raw intensity noise meets ~100 mW shot noise | 3 MHz | ~5 MHz |
| beam jitter | not yet characterized; reported to be small | characterized |
| engineering status | *~\$1M+ 1 year development* | ready |
| future development | growing market | *static to declining market* |

**Table 3-2: Modulator (Input Optics) Technical Summary**

| parameter/part | Nd:YAG Merit/*Demerit* | Argon Merit/*Demerit* |
|---|---|---|
| power handling | to 20 watts | to 5 watts |
| sensitivity | 210 volts/$\pi$, 1.06 $\mu$m | 1000 volts/$\pi$, 514 nm |
| frequency range | to 100 MHz | to 60 MHz (in pairs) |
| engineering status | commercial item | commercial item |

**Table 3-3: Core Optics Technical Summary**

| parameter/part | Nd:YAG Merit/*Demerit* | Argon Merit/*Demerit* |
|---|---|---|
| mirror size | *back mirror >27 cm* | <25 cm → <20cm |
| figure requirements (sample requirement) | Argon * $\sqrt{2}$ $=\lambda_{514}/424$ | $\lambda_{514}/600$ |
| required coating uniformity (random errors) | 0.1% | 0.1% |

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type LIGO-G950058-00- E 8-17-95

# Impact of Replacing Argon Lasers with Nd:YAG Lasers

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WWW: http://www.ligo.caltech.edu/

# Evaluation of Nd:YAG(1064nm) Lasers for Use in the Initial LIGO Interferometers

17 August 1995
Science Conference Room (818-395-2067)

- Barry Barish 0900 - 0930
  - Opening remarks & review of the charter for the trade study
- David Shoemaker 0930 - 1000
  - Review of findings with regard to TECHNICAL feasibility for using YAG lasers
- Discussion of technical issues 1000 - 1100
- Alex Abramovici 1100 - 1130
  - Review of findings with regard to IMPACT of making a change to YAG lasers
- LUNCH 1130 - 1200
- Discussion of programmatic issues 1200 - 1330

# CALIFORNIA INSTITUTE OF TECHNOLOGY

3rd F

Laser Interferometer Gravitational Wave Observatory (LIGO) Project

Rick Savage

| | |
|---|---|
| To: | LIGO/Distribution |
| From: | B. Barish and G. Sanders BCB/GHS/an |
| Phone/FAX: | Ext. 6684 and 2997 |
| Refer to: | LIGO-L950722-00-M |
| Date: | September 14, 1995 |

Subject: Lasers

We have carefully considered possible laser strategies for LIGO and are persuaded that we should switch to 1.06 $\mu$m YAG lasers, and that this should be accomplished as quickly as possible. We believe the long term benefits to LIGO of making this switch now are considerable and are well aware of the shorter term impacts of this change. Success, therefore, depends on working together to quickly and effectively affect this change, to acquire and gain experience with YAG lasers and to research our R&D and detector programs to minimize the scheduling and other short-term impacts. To do this we must build a very strong YAG effort and we must aggressively and creatively work all the issues involved in the switch. To accomplish this, we have asked Stan Whitcomb (and he has agreed) to lead our effort on the YAG and we promise him our strong support. As soon as Stan can describe a plan for the effort the LIGO Change Control/Technical Board will be asked to formally review this change to the baseline.

This YAG decision has been made following a process that began with a presentation (at our request) by David Shoemaker at the May 1995 Science-Integration meeting. We followed that by tasking Shoemaker and Abromovici to do a more quantitative study resulting in a technical note. We invited all to participate in a discussion meeting on August 17, 1995. Following that meeting, we invited individual input and received many thoughtful replies.

There are many complex issues involved in this decision and judgement is involved in making the final decision. We have weighed heavily the long term objectives of finding the clearest path toward reaching and exceeding the initial design sensitivity of LIGO. Although others weighed different factors more heavily, we can report that there is a near consensus on whether we should make the switch.

With this decision behind us, it is crucial that now we all get behind it and work together to make it work. In a large group effort like LIGO it is essential that we bring out hard issues, carry out an open process to evaluate them, make carefully considered decisions, and then that we all get behind the decision and move on.

We thank everyone for their hard work, thoughtful input, and in advance, for their support of this important LIGO decision.

BCB:dt

cc: Chronological File
Document Control Center

*InterOffice Memorandum*

• May 15, 1996.

# FIXED-PRICE CONTRACT
## Contract No. PC198201

BETWEEN

CALIFORNIA INSTITUTE OF TECHNOLOGY
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PASADENA, CALIFORNIA 91125

AND

LIGHTWAVE ELECTRONICS CORPORATION
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Design and Fabrication of Nd3+ Lasers

IS A

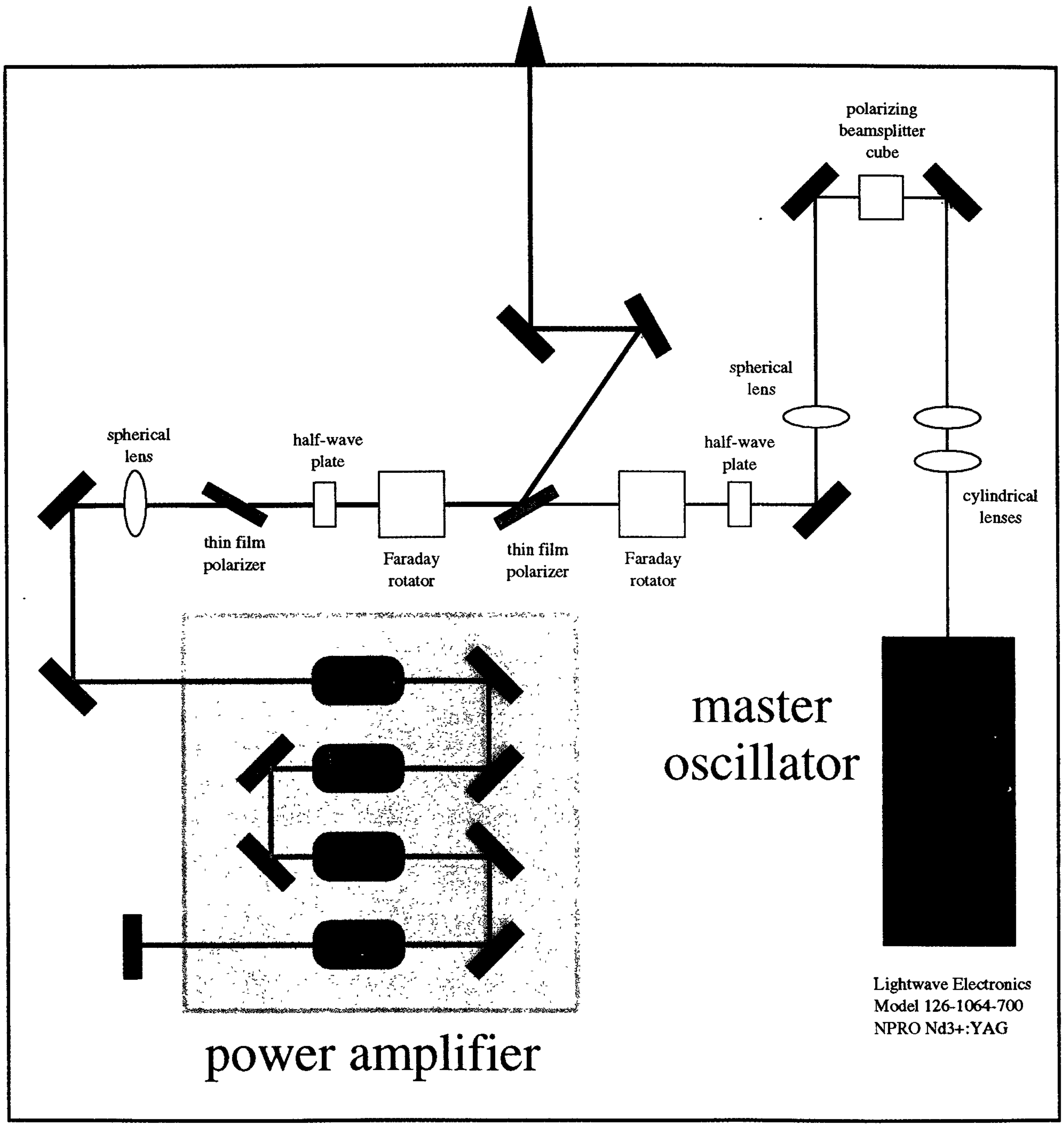
SUBCONTRACT UNDER A NATIONAL SCIENCE FOUNDATION
COOPERATIVE AGREEMENT NO. PHY-9210038

CONTRACT PRICE: $735,424.00

LIGO-C960880-A-R

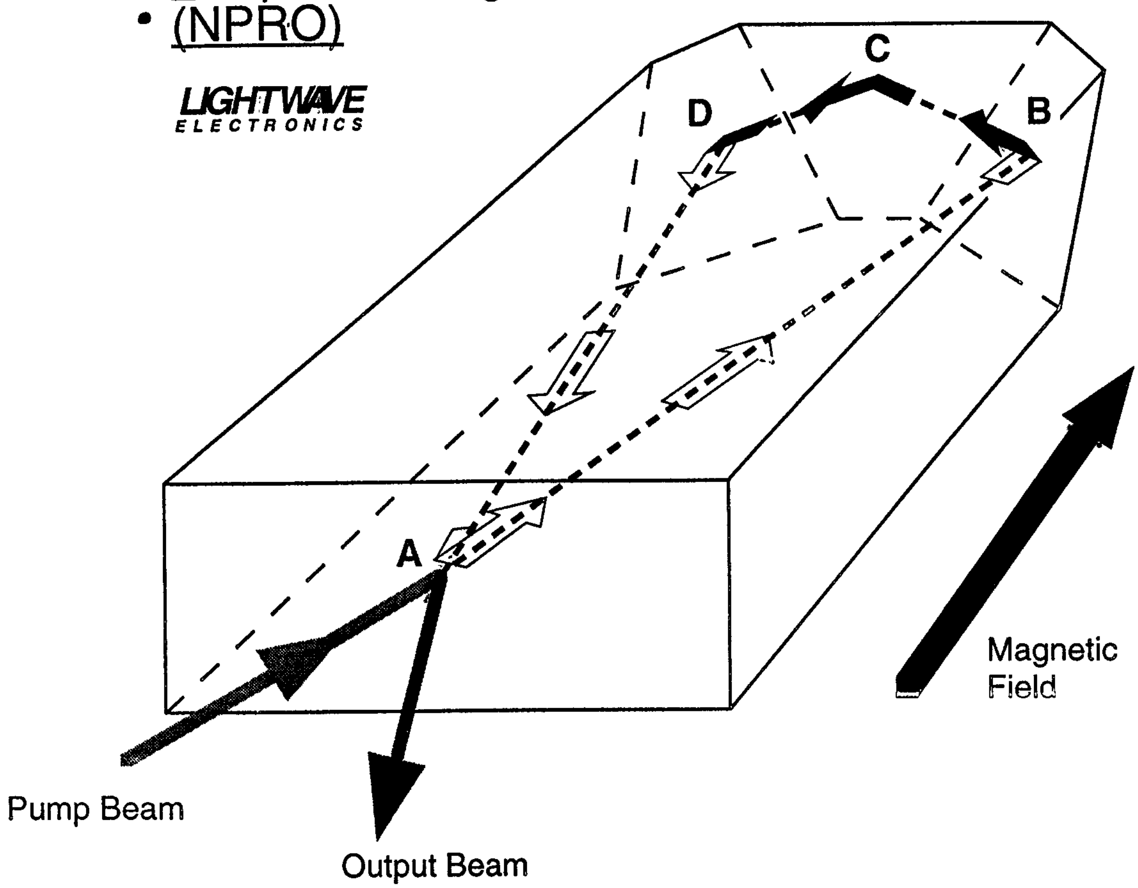
- 3 10-W Lasers
- option for up to 5 additional Lasers

# LIGO 10-W Laser Schematic Diagram



## Nonplanar Ring Oscillator (NPRO)

LIGHTWAVE ELECTRONICS




Magnetic field enforces unidirectional operation.

Unidirectional operation leads to single-frequency oscillation.

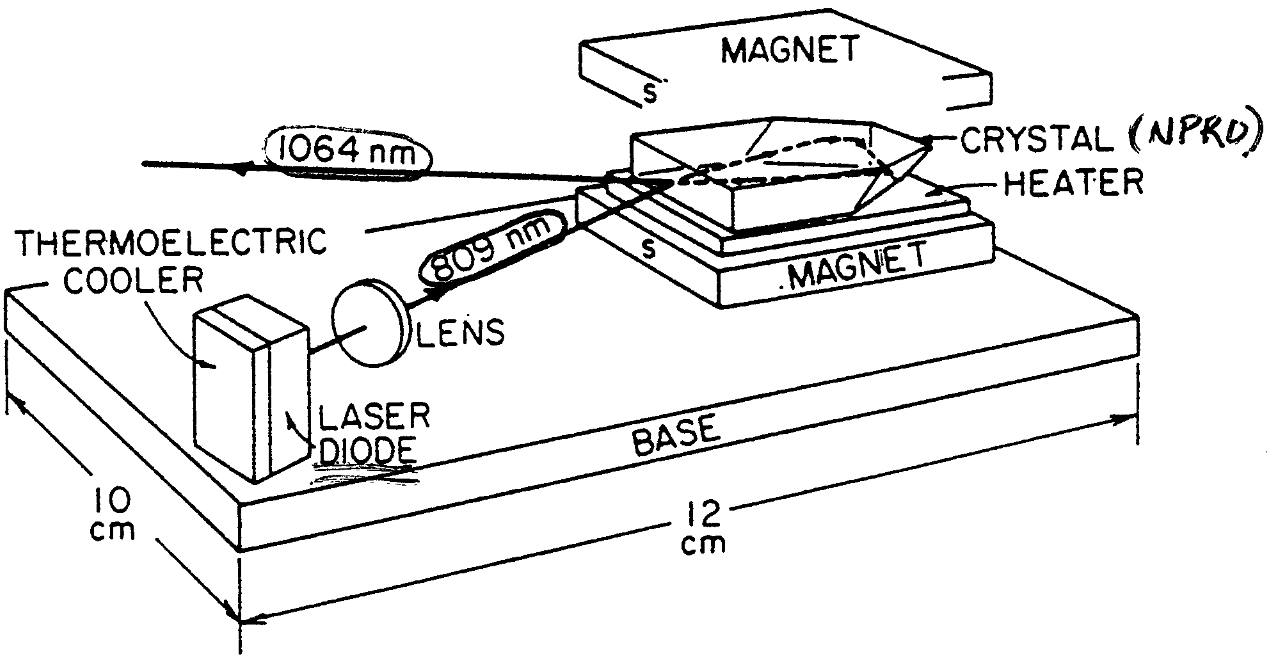
Monolithic crystal design leads to stable frequency.

No efficiency penalty relative to multi-mode lasers.

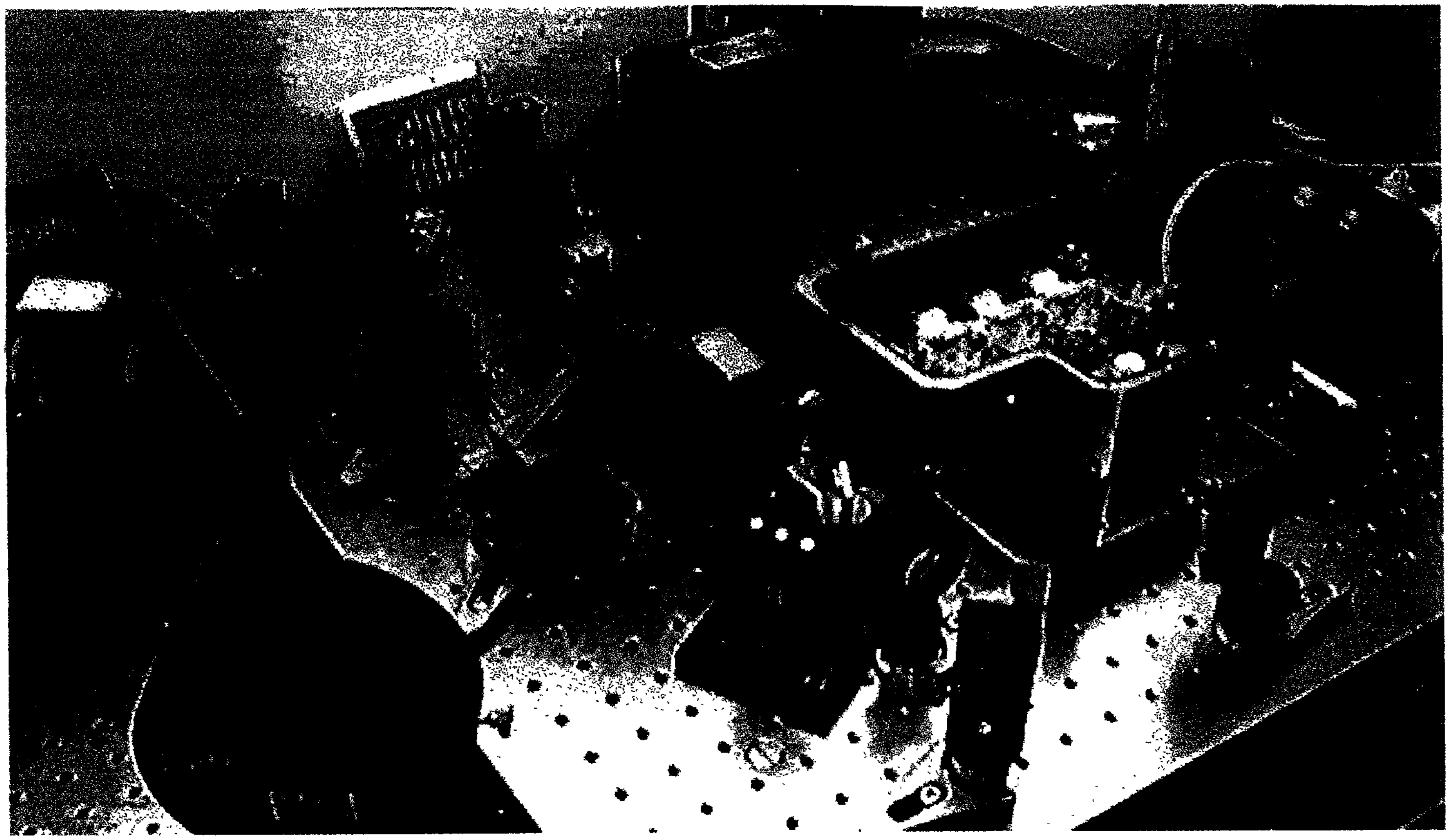
Length of crystal: 3 mm   Output power: 50 mW

Z ~ .31"  FSR = 8.6 GHz

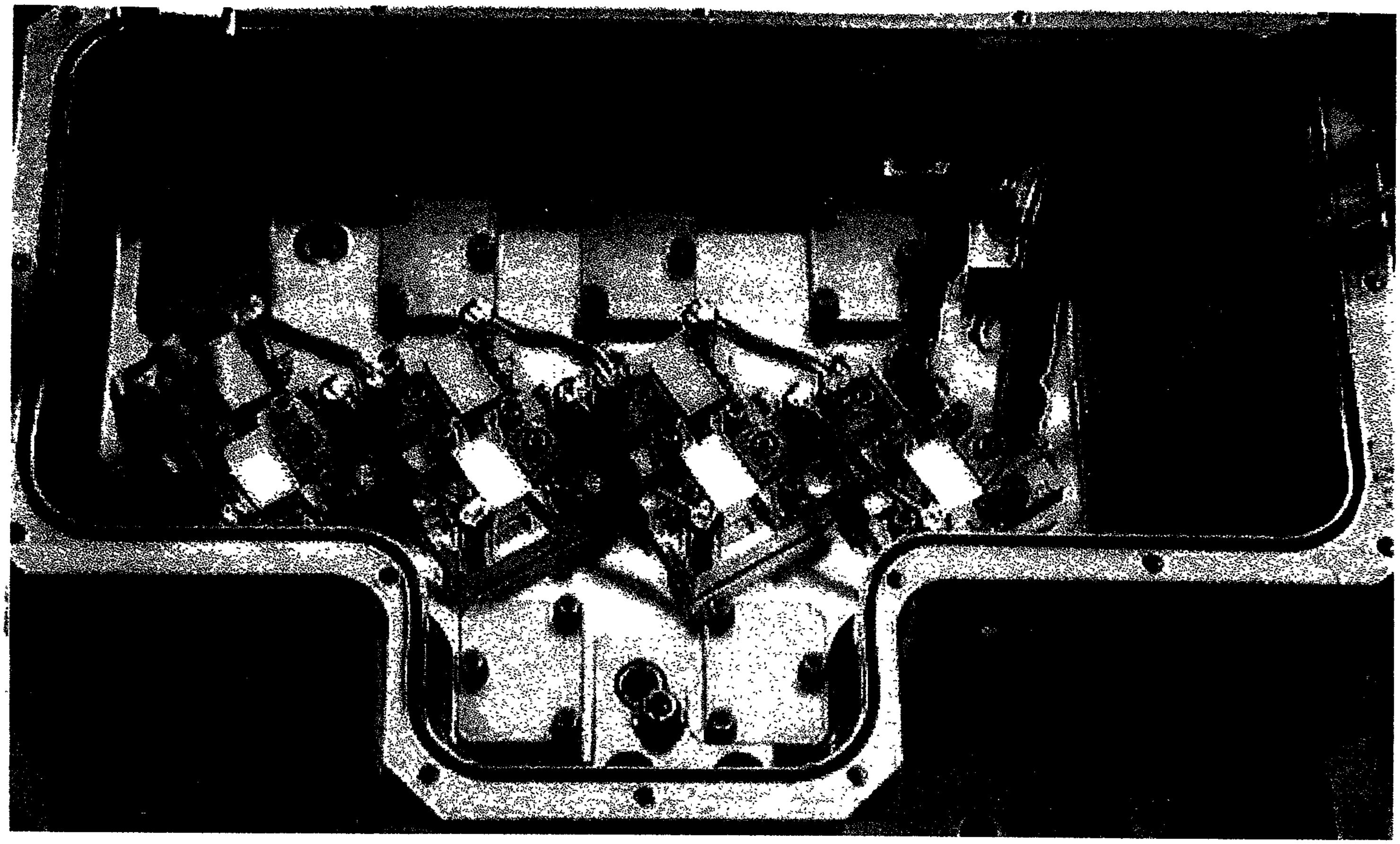
Laser diode pumped, NPRO based master oscillator




- Frequency tuning via
  - NPRO thermoelectric cooler
  - Piezoelectric transducer mounted to xtal.
- Output power tuning via pump laser diode current adjustment
- 700 mW output power (600 mW required for 10-W laser).



8/29/97



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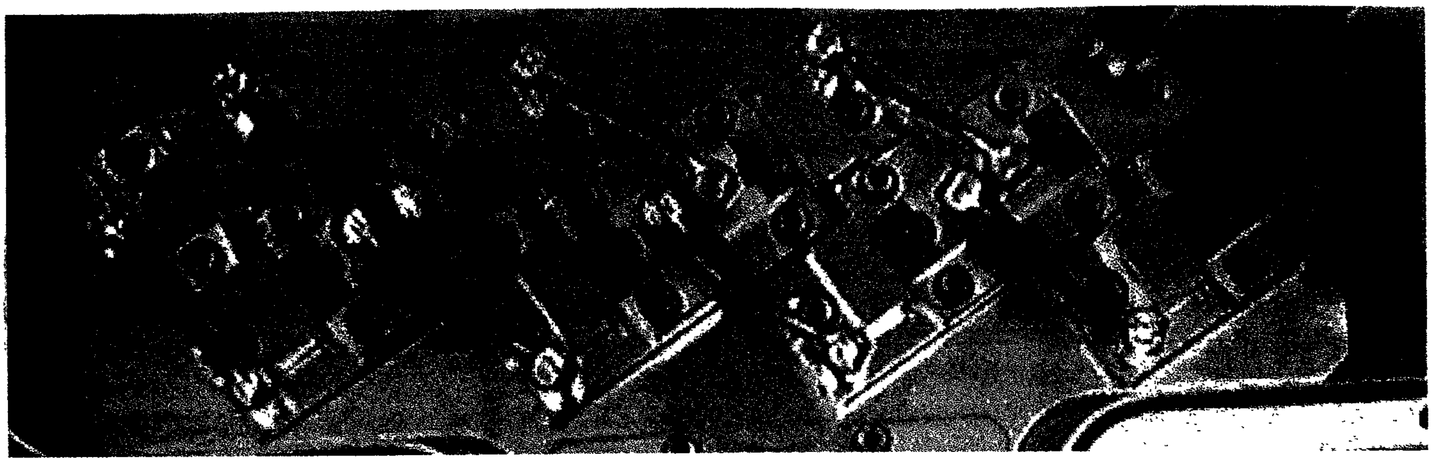
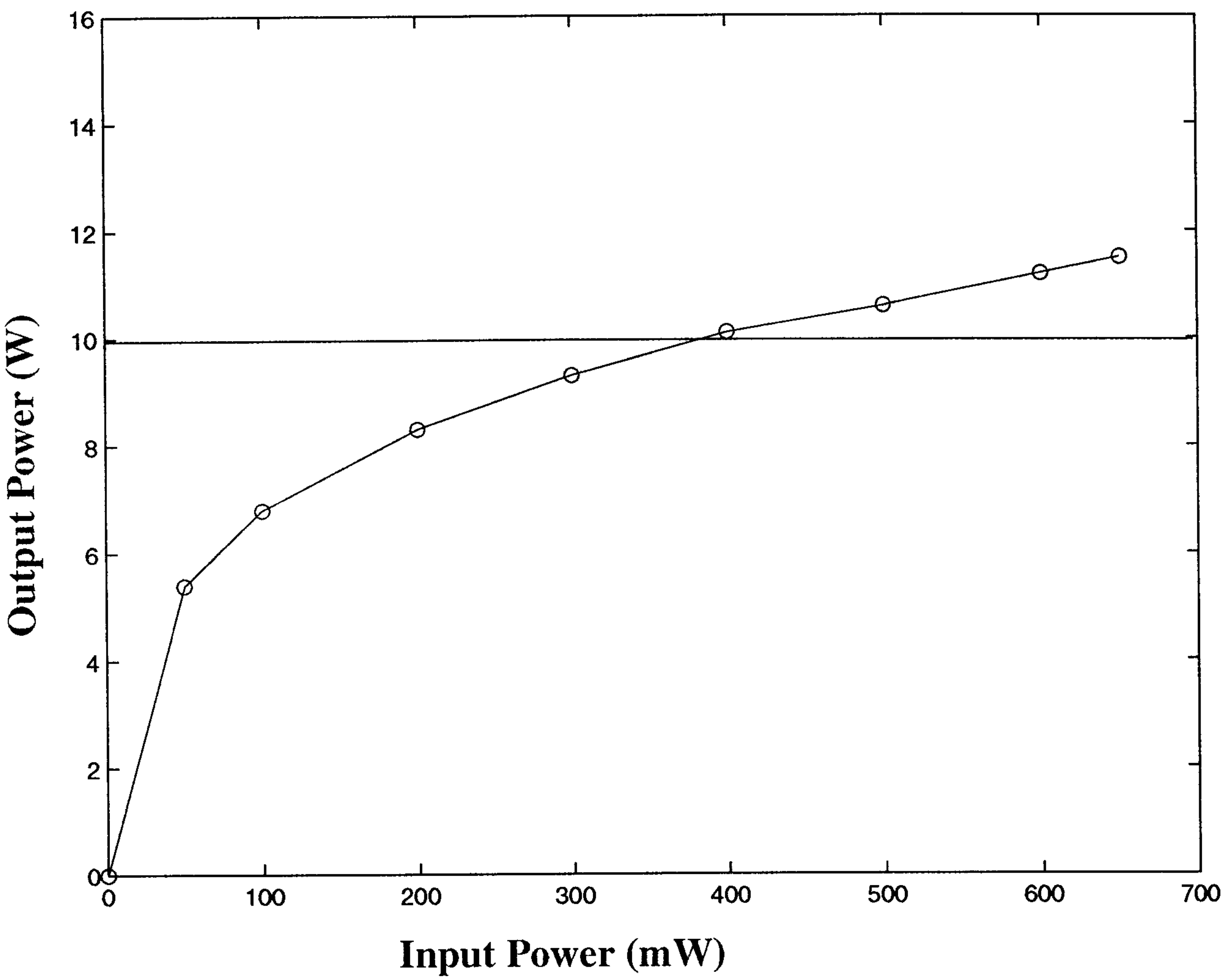


8/29/97

# LIGO 10-W Laser Brassboard Unit Data

Double-Pass Output Power



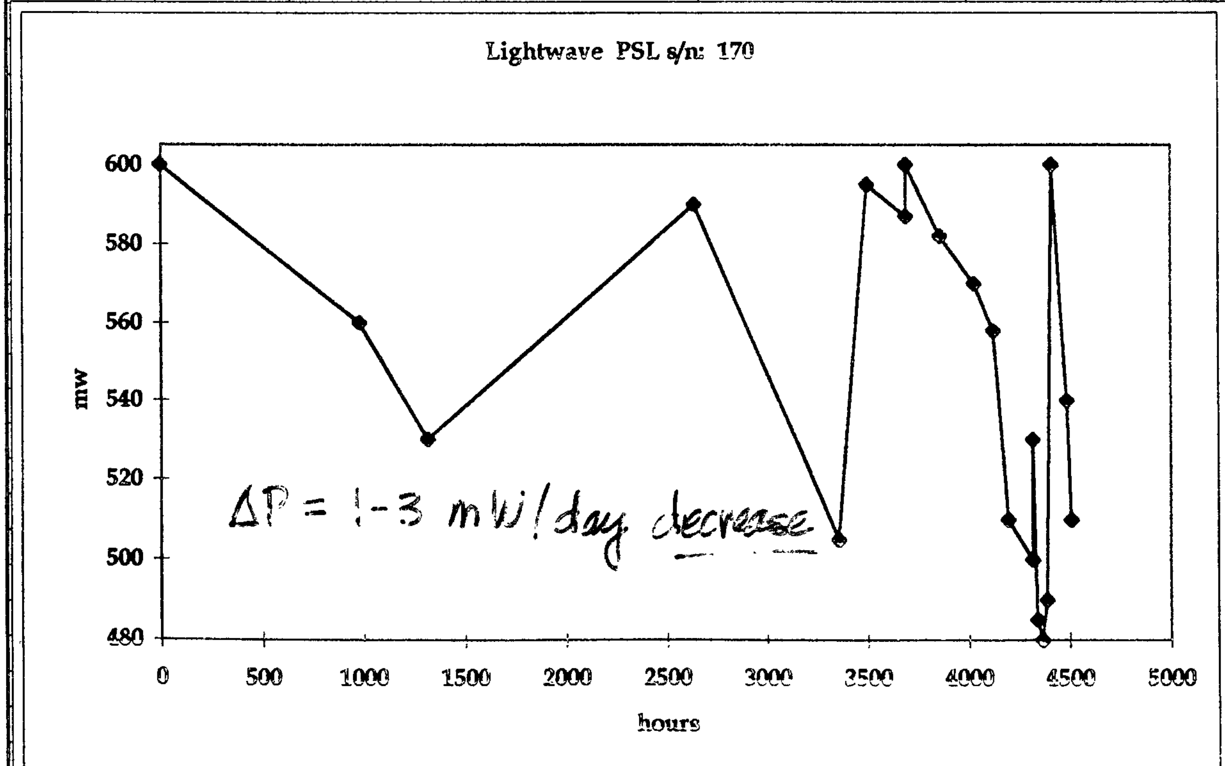
# LIGO 10-W Laser Performance Requirements

- $> 10$ W in circular $TEM_{00}$ mode
  - $< 1$ W total in all non-$TEM_{00}$ modes
- Relative power fluctuations $< 10^{-5}\ (\mathrm{Hz})^{-1/2}$
  - 100 Hz to 10 kHz
- Within 2 dB of shot noise limit for 10 mA of photodetected current ( $7 \times 10^{-9}\ (\mathrm{Hz})^{-1/2}$ )
  - Above 24.5 MHz
- Frequency fluctuations $< 500 \times (100/f)\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
  - 100 Hz to 10 kHz
- Relative pointing angle fluct. $< 3 \times 10^{-6}\ (\mathrm{Hz})^{-1/2}$
  - Above 150 Hz
- 10,000 Hours Mean Time Between Failures

Power Measurement
lightwave
PSL - NPRO 126 S/N: 170

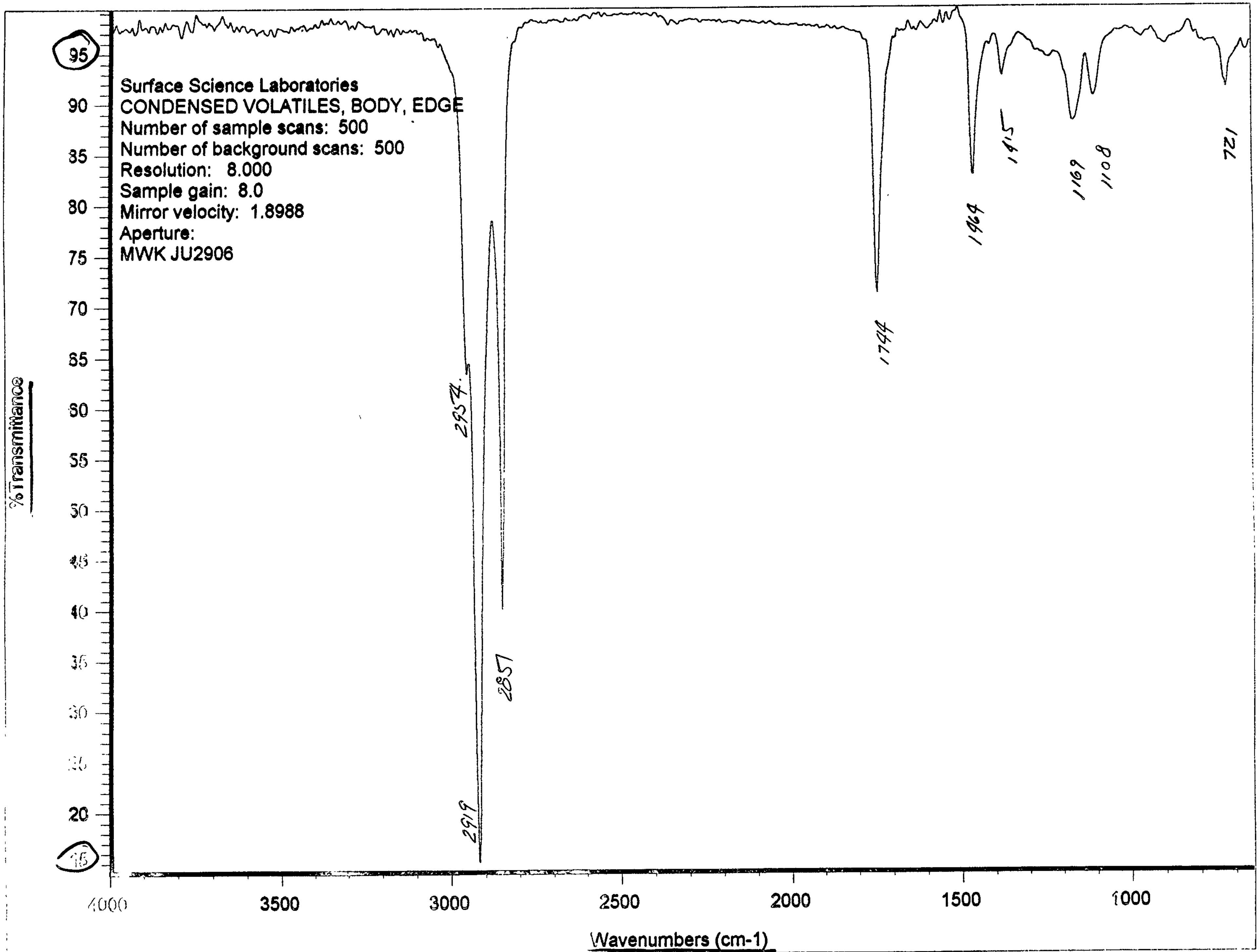


| Date | Hours | Power Meter | Power Control | mw/day | Current | Adj. | psl |
|---|---|---|---|---|---|---|---|
| | | (mw) | (mw) | | (amps) | | |
| 11/27/96 | 0 | 600 | 600 | | 2.52 | 0 | |
| 1/7/97 | 984 | 560 | 600 | | 2.52 | 0 | |
| 1/21/97 | 1320 | 530 | 600 | | 2.52 | 0 | |
| 3/18/97 | 2640 | 590 | 595 | | 2.52 | 0 | |
| 4/17/97 | 3360 | 505 | | | 2.52 | adj | |
| 4/23/97 | 3504 | 595 | 600 | | 2.54 | 0 | |
| 5/1/97 | 3696 | 587 | 570 | | 2.54 | 0 | |
| 5/1/97 | 3696 | 600 | 585 | | 2.54 | adj | |
| 5/8/97 | 3864 | 582 | 570 | | 2.54 | 0 | |
| 5/15/97 | 4032 | 570 | 555 | | 2.54 | 0 | |
| 5/19/97 | 4128 | 558 | 548 | | 2.54 | 0 | |
| 5/22/97 | 4200 | 510 | 511 | | 2.5 | 0 | |
| 5/27/97 | 4320 | 500 | 496 | | 2.5 | 0 | off |
| 6/2/97 | 4320 | 530 | 526 | | 2.54 | 0 | on |
| 6/3/97 | 4344 | 485 | 489 | | 2.5 | 0 | |
| 6/4/97 | 4368 | 480 | 489 | | 2.5 | 0 | |
| 6/5/97 | 4392 | 490 | 503 | | 2.5 | 0 | |
| 6/6/97 | 4416 | 600 | 600 | | 2.775 | adj | |
| 6/9/97 | 4488 | 540 | 548 | | 2.775 | 0 | |
| 6/10/97 | 4512 | 510 | 526 | | 2.775 | 0 | fail! |
| | | | | | | | |
| from 5/01 - 6/5/97 | | overall 696 hrs | POWER LOSS= | 3.7931034 | mw/day | | |

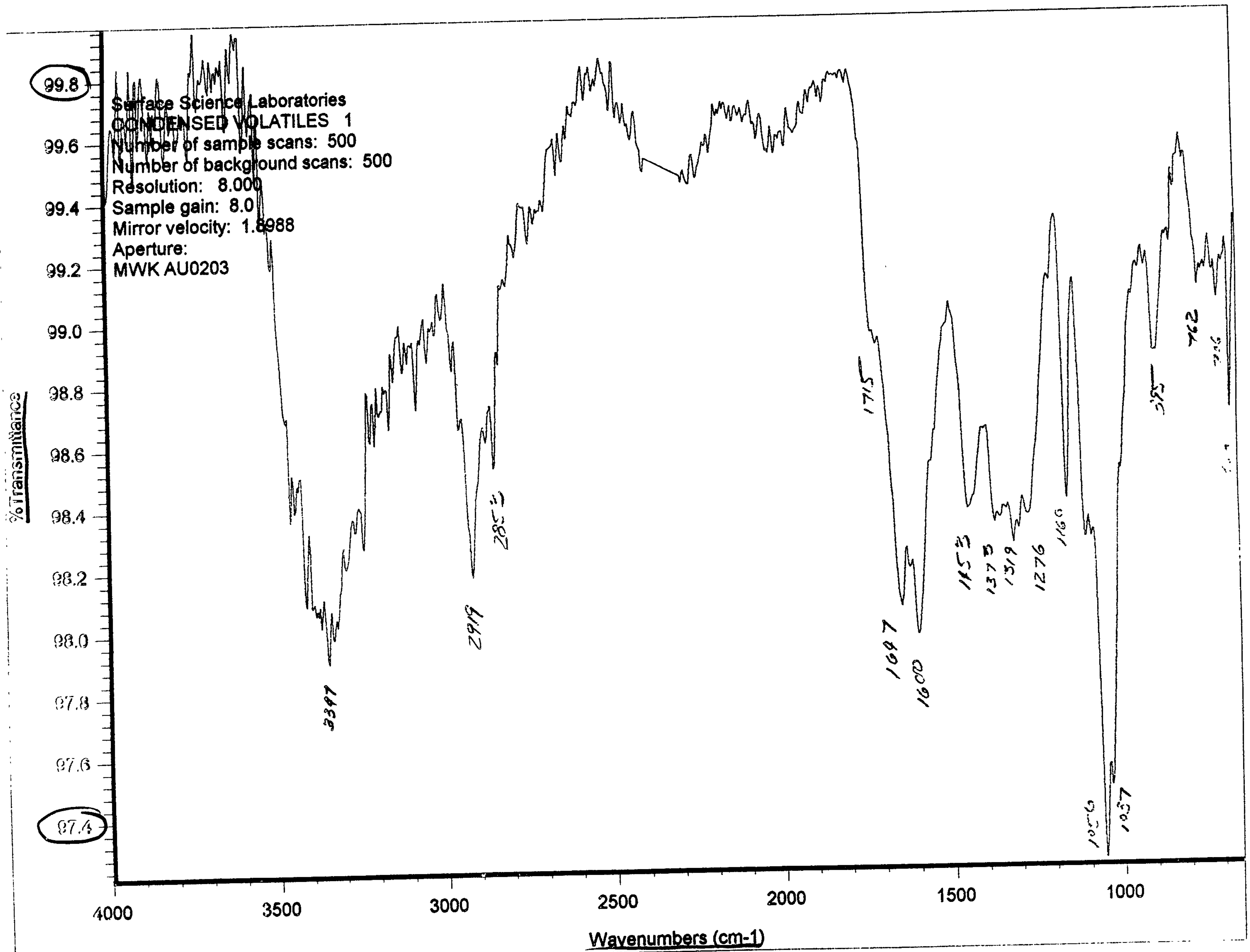


# Lightwave Model 126 Reliability Investigations - Completed

- baseline condensable volatiles test 6/18/97
  - silicones, machine oil, circuit board additives
    - → more agressive cleaning, bake out.
- elimination of thermal grease and apiezon grease from build procedure 6/20/97
- baseline gas chromatography / mass spectrometry 6/27/97
  - siloxanes and cleansers
    - → improved cleaning and bake out
- non-destructive analysis results from SDL 7/1/97
  - light burn spot on facet, contamination on facet
- improved cleaning and bake out procedures implemented 8/1/97
  - machined parts degreased and baked 100°C / 1 hour
  - electronics boards 100°C / 3 hours
- condensable volatiles test after new cleaning procedures 8/12/97
  - contaminants greatly reduced
- condensable volatiles test after 24 hour bake at 85°C 8/12/97
  - no contaminants detected


95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
%Transmittance
Surface Science Laboratories
CONDENSED VOLATILES, BODY, EDGE
Number of sample scans: 500
Number of background scans: 500
Resolution: 8.000
Sample gain: 8.0
Mirror velocity: 1.8988
Aperture:
MWK JU2906
2954
2919
2857
1744
1464
1415
1169
1108
721
4000
3500
3000
2500
2000
1500
1000
Wavenumbers (cm-1)

- June 18, 1997



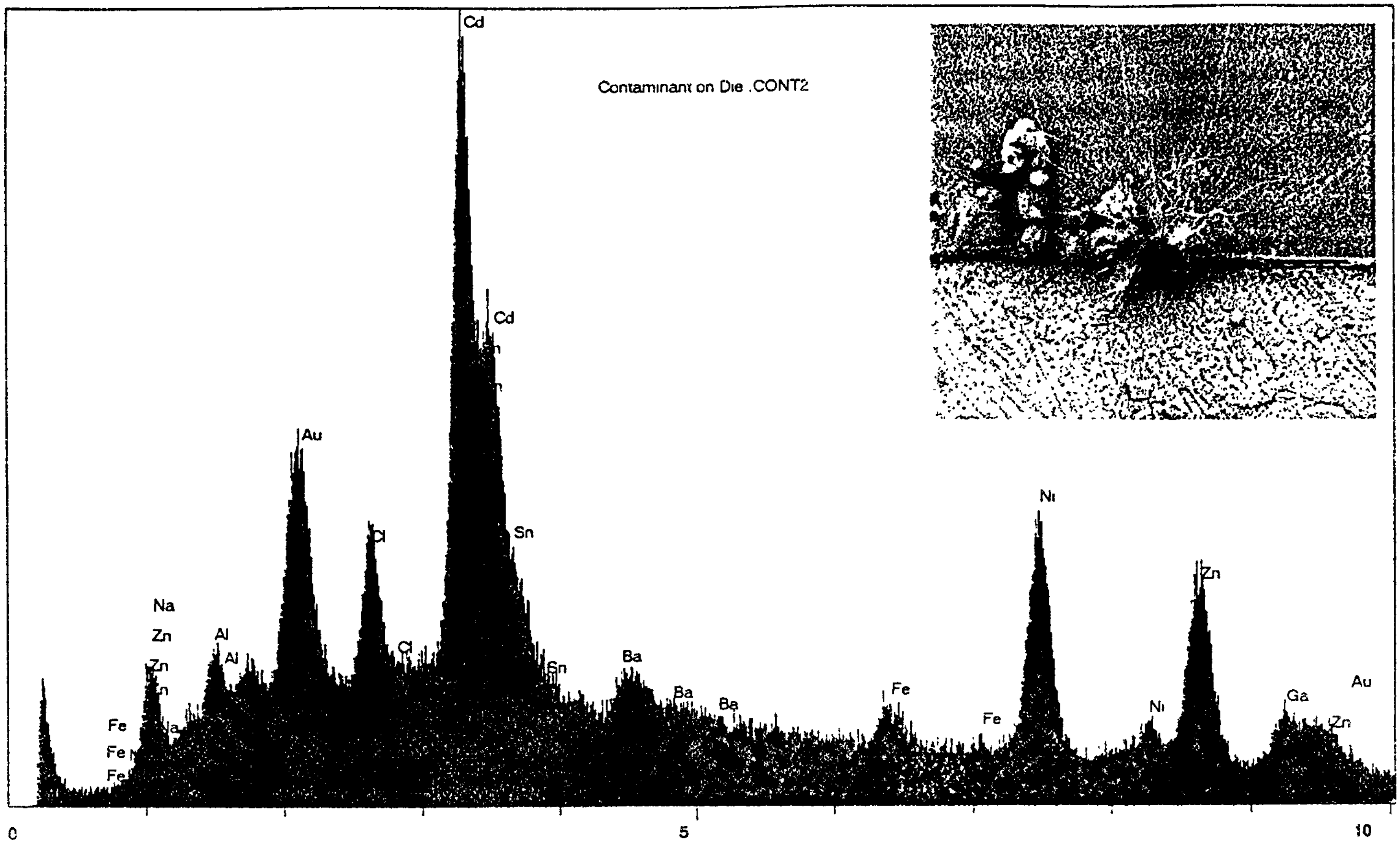

4 - August 12, 1997

# Lightwave Model 126 Reliability Investigations    Planned.

- condensable volatiles test just above facet    8/14/97
  - waiting for test results
- development of better cleaning and bake out procedures    8/15/97
- degrading and new SDL diodes to JPL for surface analysis    8/22/97
  - in progress
- SDL / Lightwave 40-diode test    7/24/97. agreement date
  - 20 diodes built into Model 126 lasers
    20 diodes run and monitored at SDL
- diode lifetime testing at Lightwave
  - 2 diodes to be tested in Model 126 packages
  - 2 diodes in 126 package but w/o collection lens *
  - 2 diodes in hermetic package from SDL
  - 1 diode from an alternate vendor

one unit has been operating for 28 days with no change (<1%).

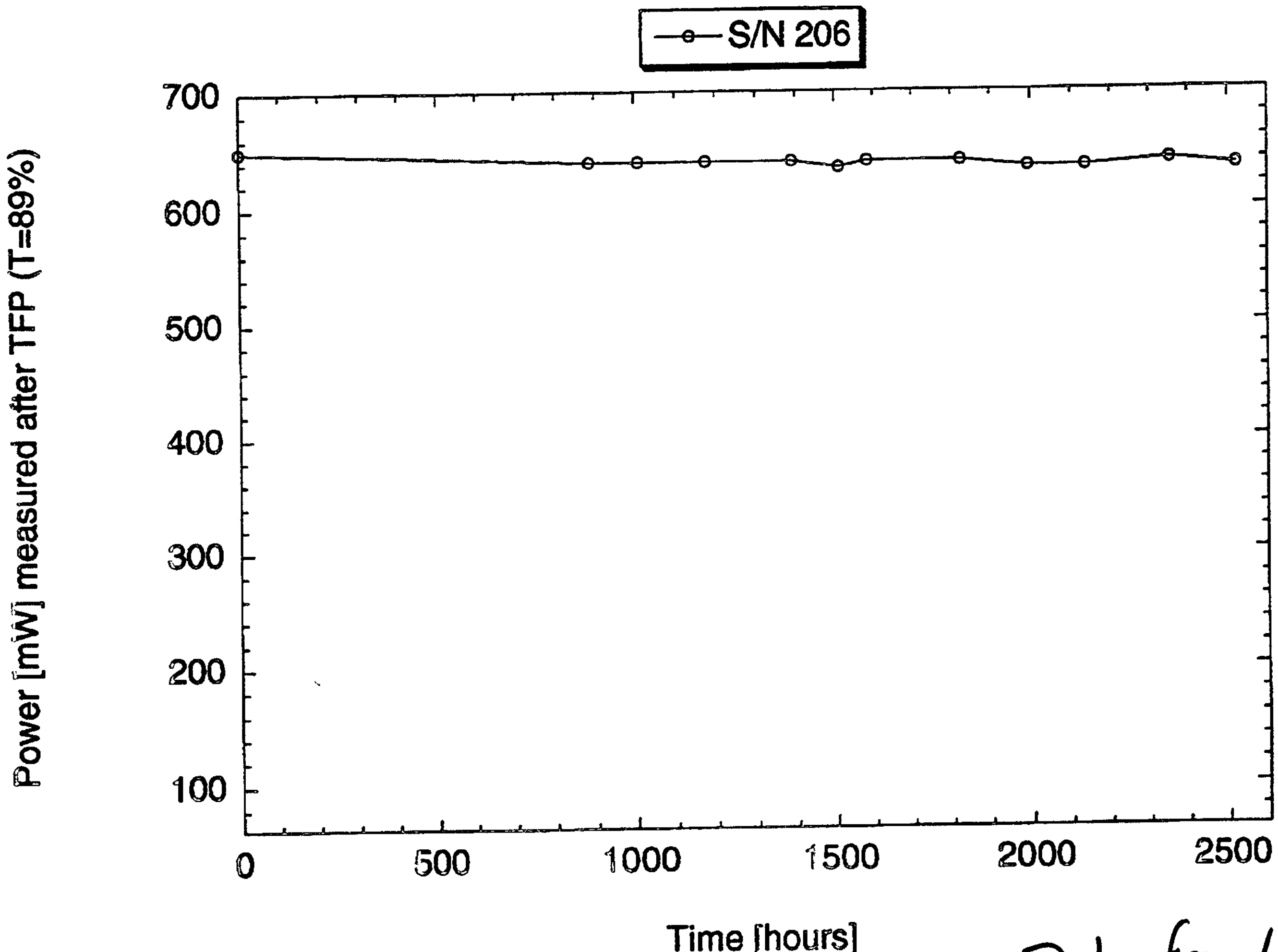
- lifetime testing of Model 126 lasers for LIGO 10-W lasers
  - 4 units under test
    - 3 built before new procedures
    - 1 with improved cleaning and bake



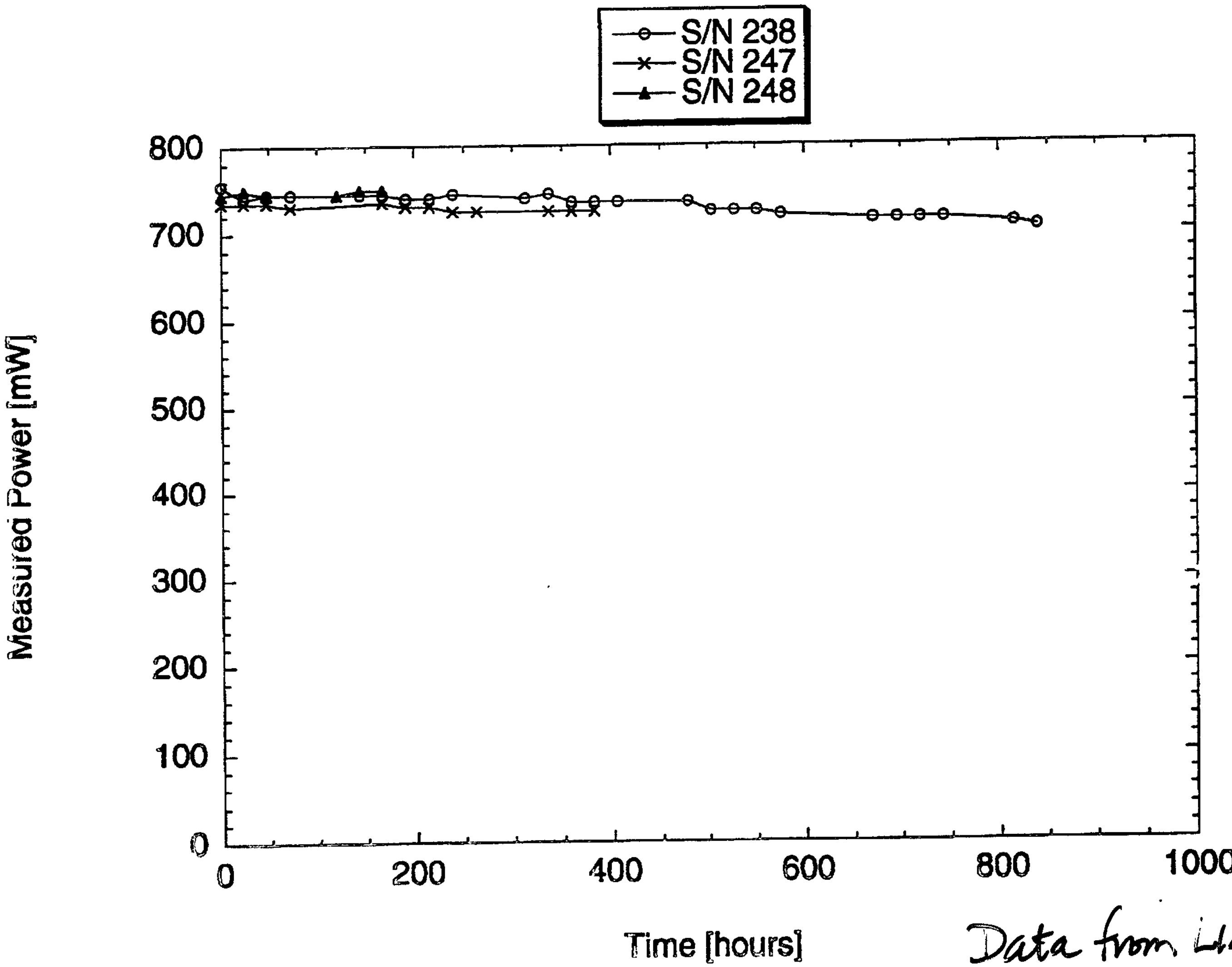

Cursor1.080 keV 297 cnt ID =
Vert=2050 Window 0.000 - 40.950 339422 cnt

Sm ma2, Sm ma1, Ce mg1, Ce mg2, Na kb1, Er mz2

Surface analysis (SEM) performed by Seal Labs (with John Klotcher Also reliability).

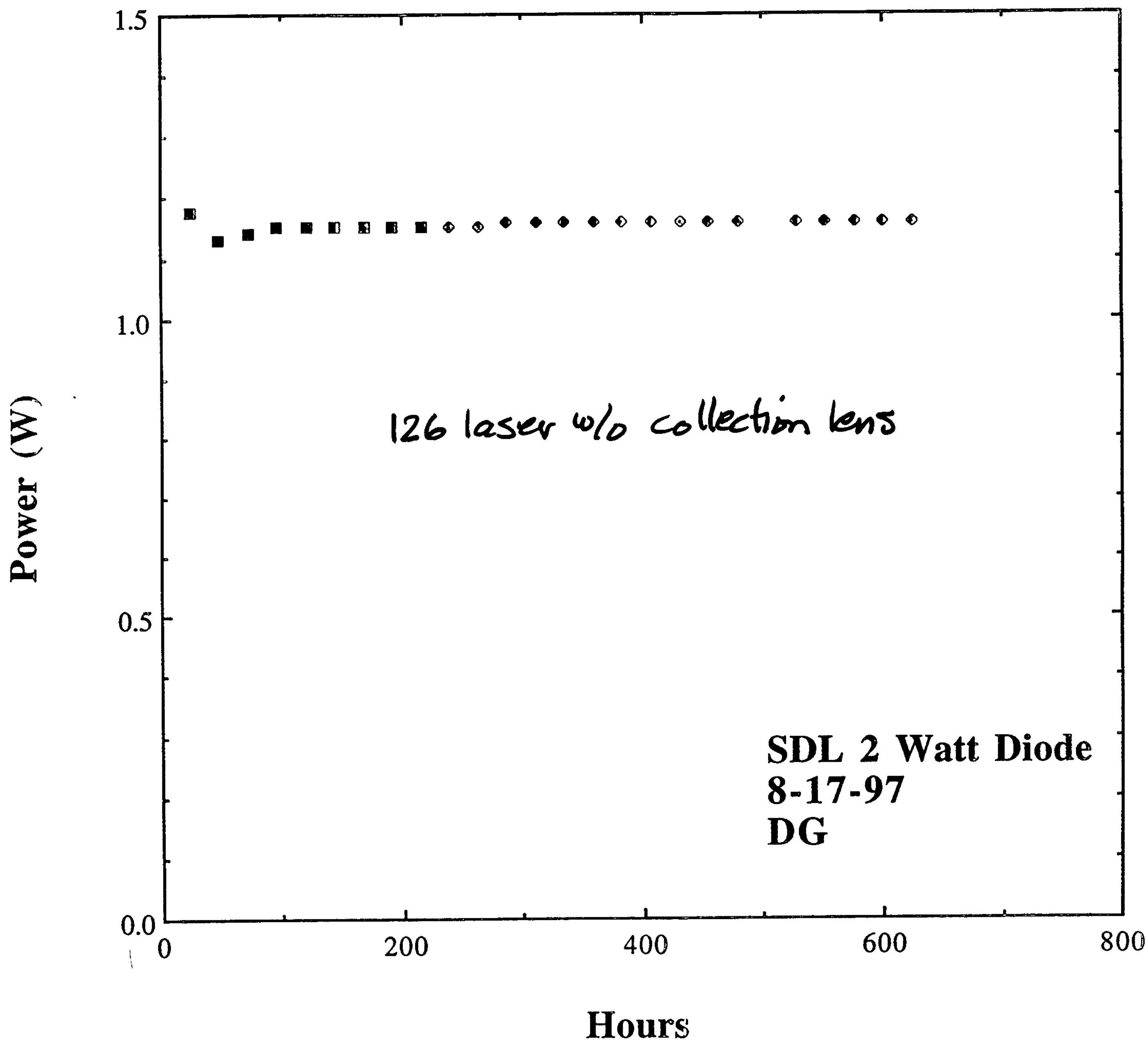



Data from Lightwave

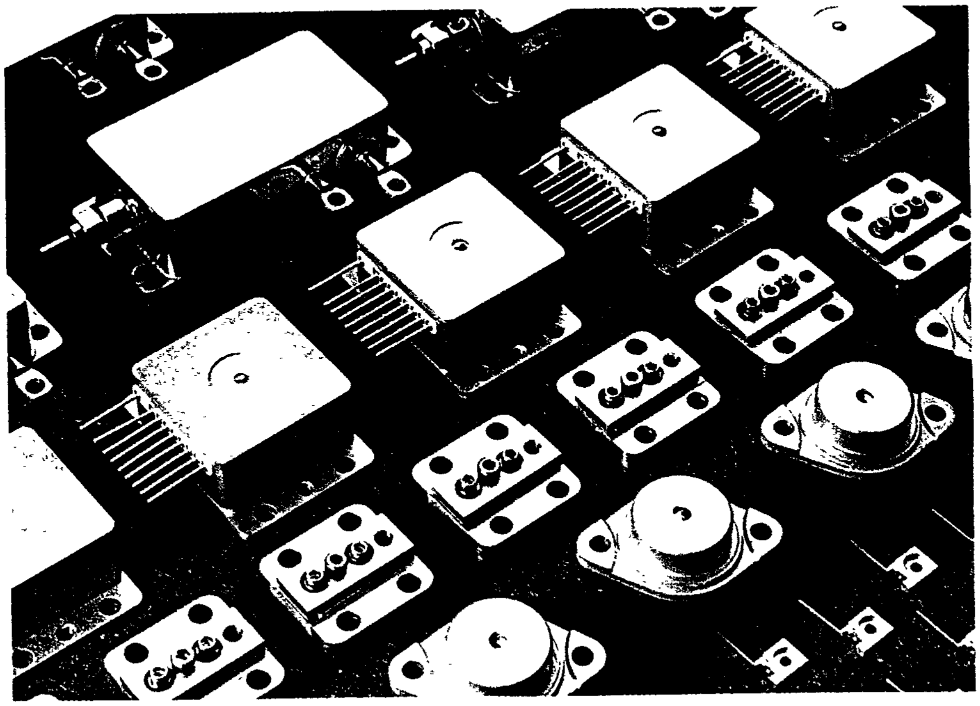



Data from Lightwave.

# Diode Lifetest #1



# Longer Lifetimes. Choice of Wavelengths. On-Time Delivery.



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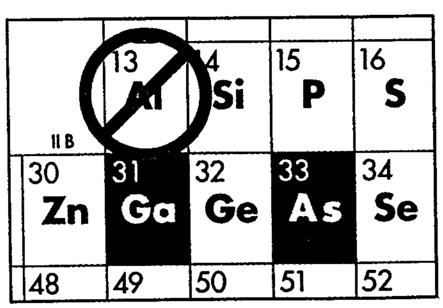


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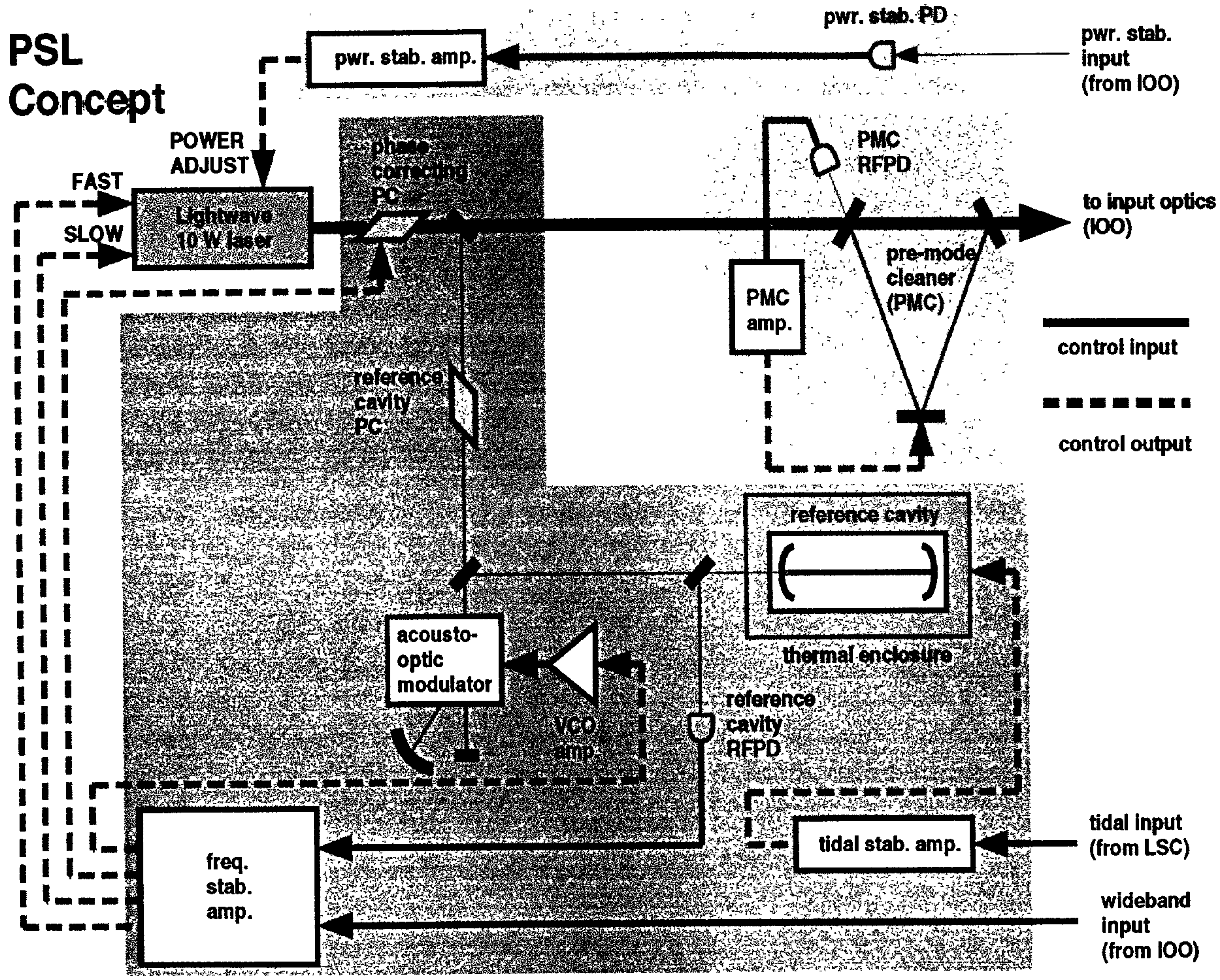
Germany +49 (6071) 9680 • United Kingdom +44 (1223) 424065

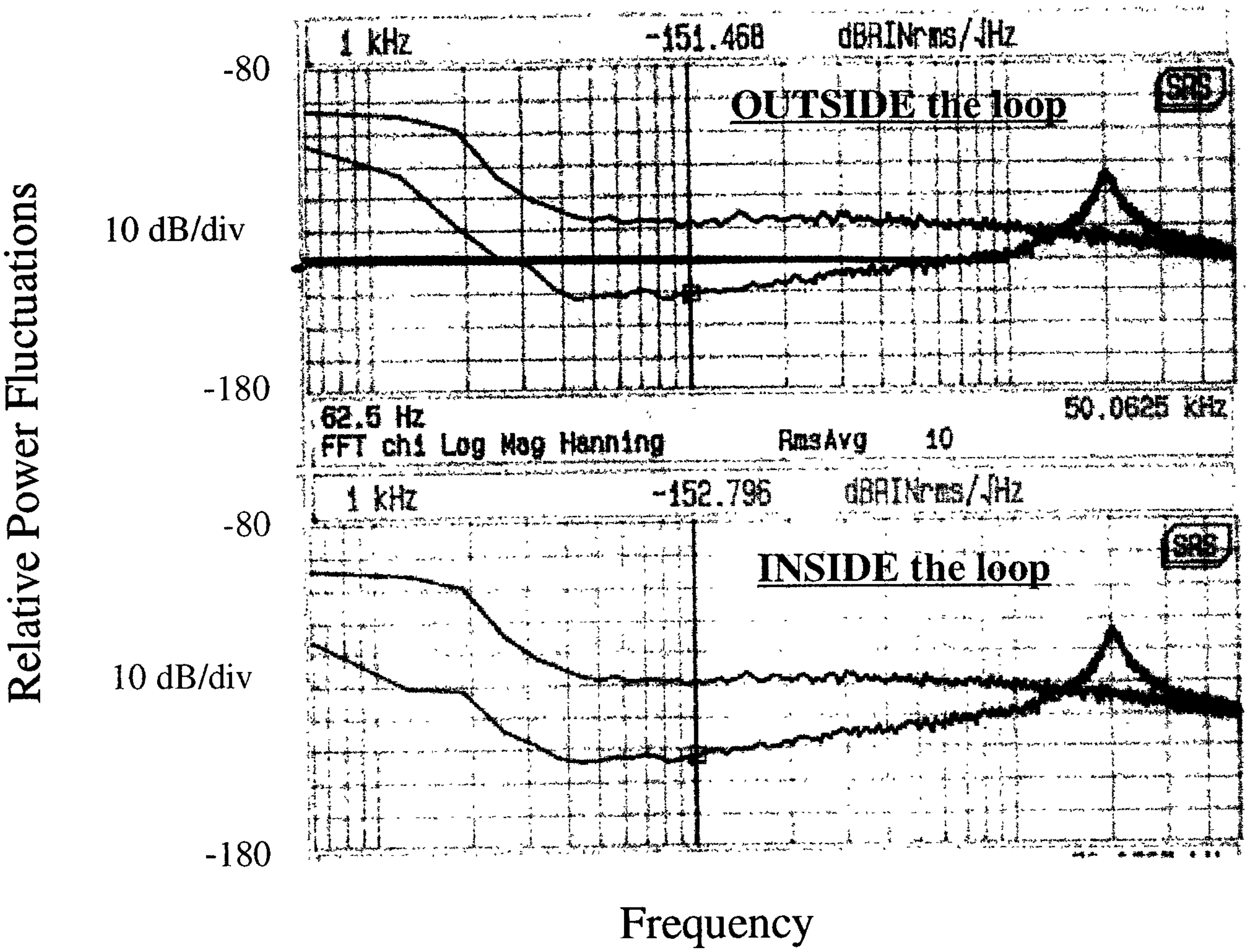
# Pre-stabilized Laser Performance Requirements

- Output power:
  - $> 8.5$ W in circular $TEM_{00}$ mode
- Beam Quality:
  - $< 100$ mW total in all non-$TEM_{00}$ modes
- Relative power fluctuations in GW Band:
  - $< 10^{-7}\ (Hz)^{-1/2}$ from 100 Hz to 10 kHz
- Relative Power Fluctuations Above 24.5 MHz:
  - $< 1.005$ x shot noise limit for 600 mW laser power
- Frequency fluctuations:
  - $< 0.1 \times (100/f)\ Hz/\sqrt{Hz}$ from100 Hz to 1 kHz
- Beam Relative Pointing Angle Fluctuations:
  - $< 2 \times 10^{-6}\ (Hz)^{-1/2}$

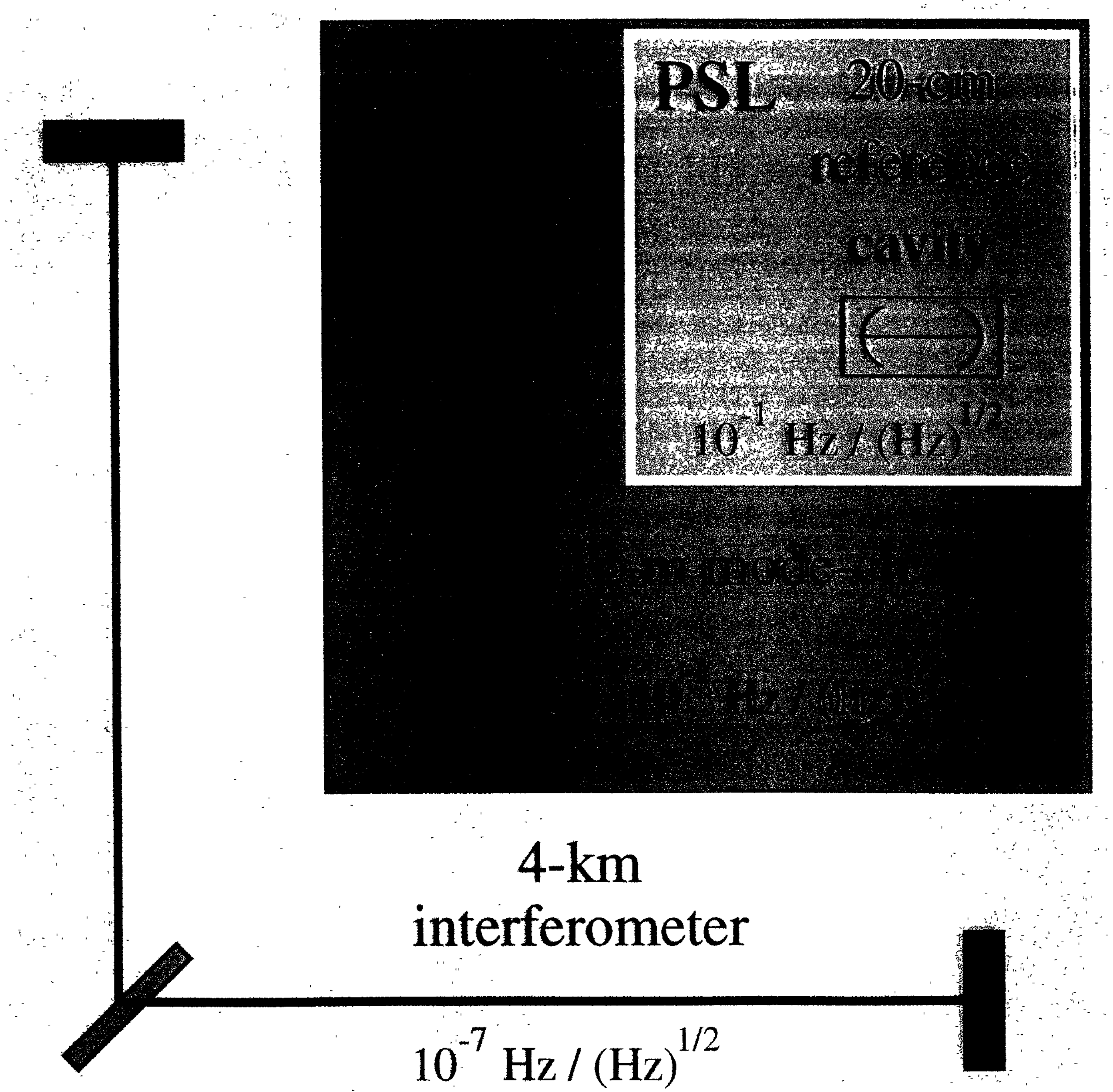
# Pre-stabilized Laser System Schematic Overview



# Measured Relative Power Fluctuations
# NPRO Pre-Stabilized Laser Data

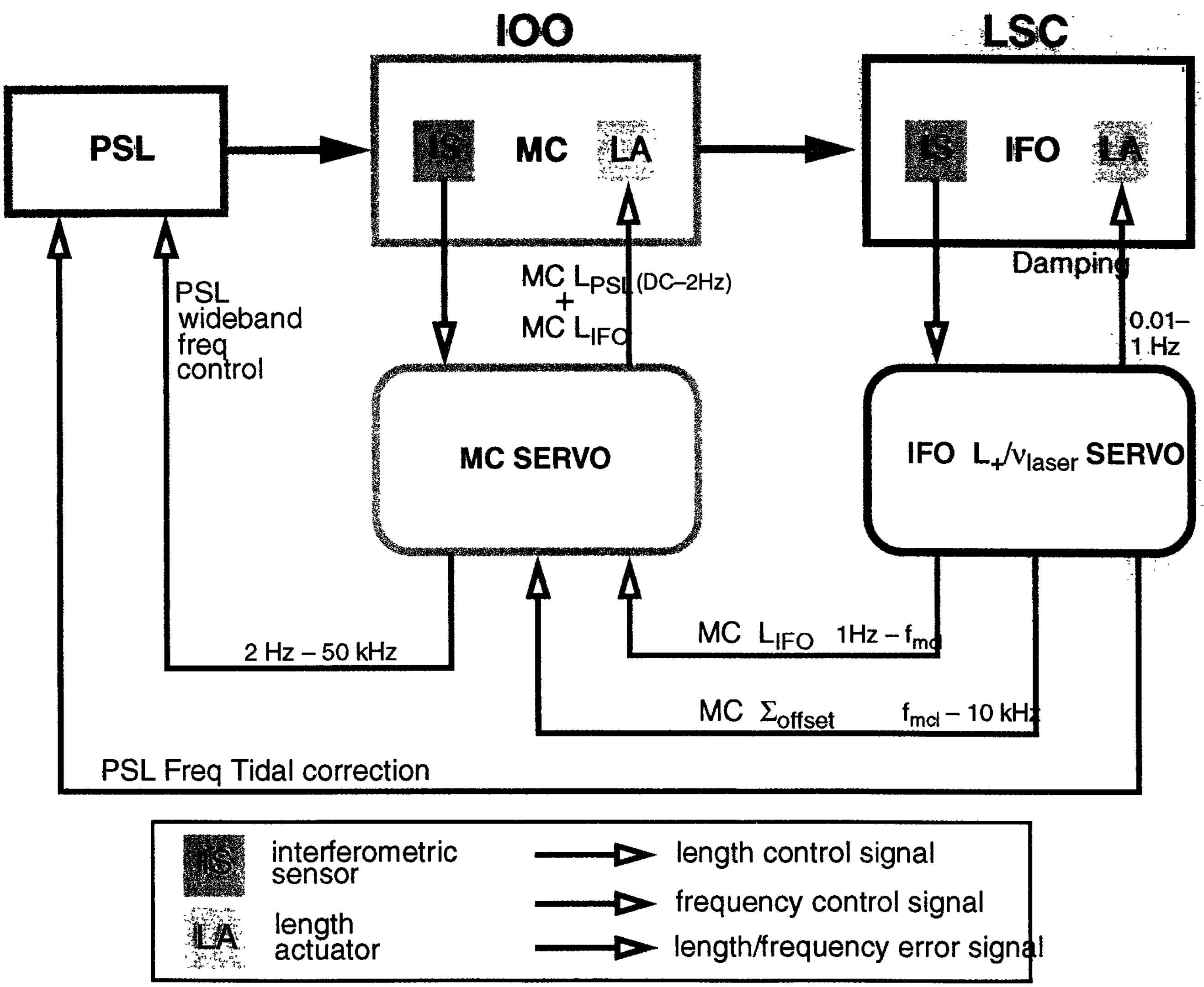


# LIGO Frequency Stabilization Strategy
# Three Nested Loops

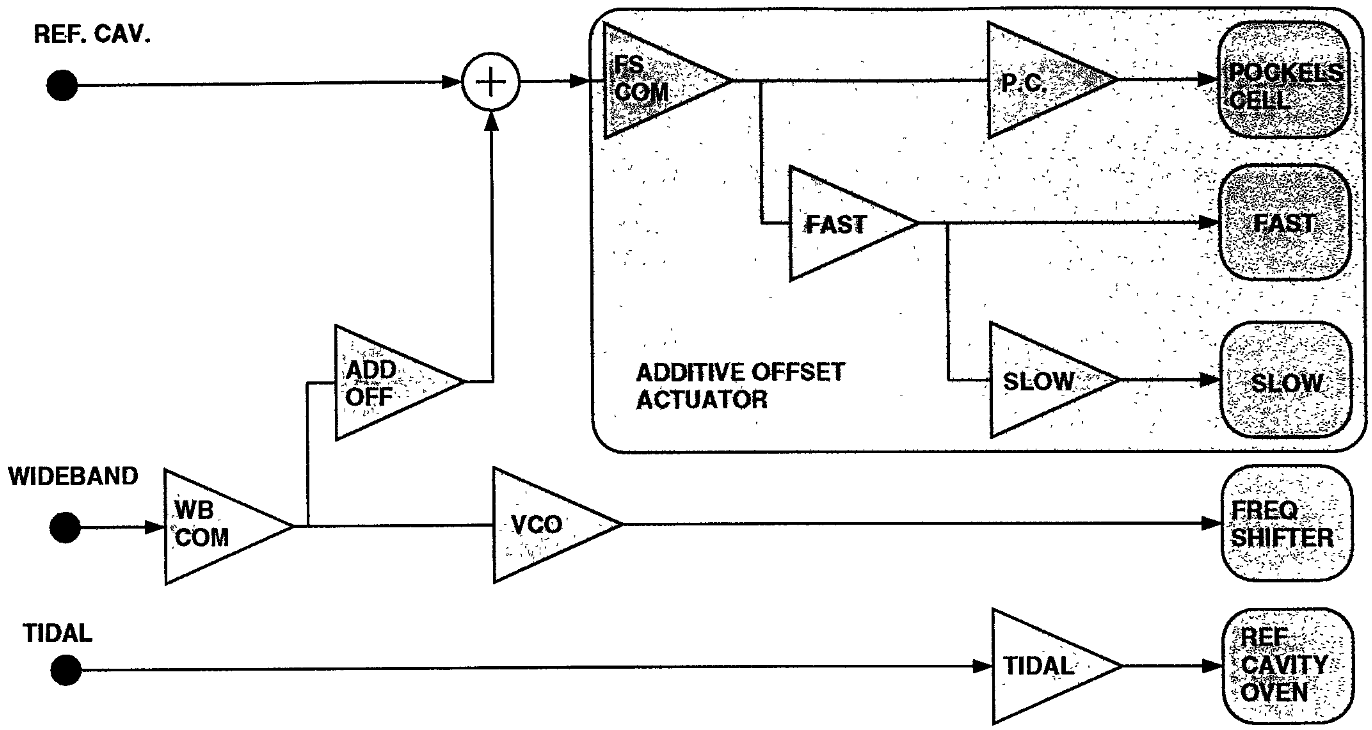


# LIGO Frequency Stabilization Control Topology

$10^{-1}$ Hz/$\sqrt{\text{Hz}}$ ⟶ $10^{-4}$ Hz/$\sqrt{\text{Hz}}$ ⟶ $10^{-7}$ Hz/$\sqrt{\text{Hz}}$



# Pre-stabilized Laser
# Frequency Stabilization Strategy




PSL Frequency Control Concept

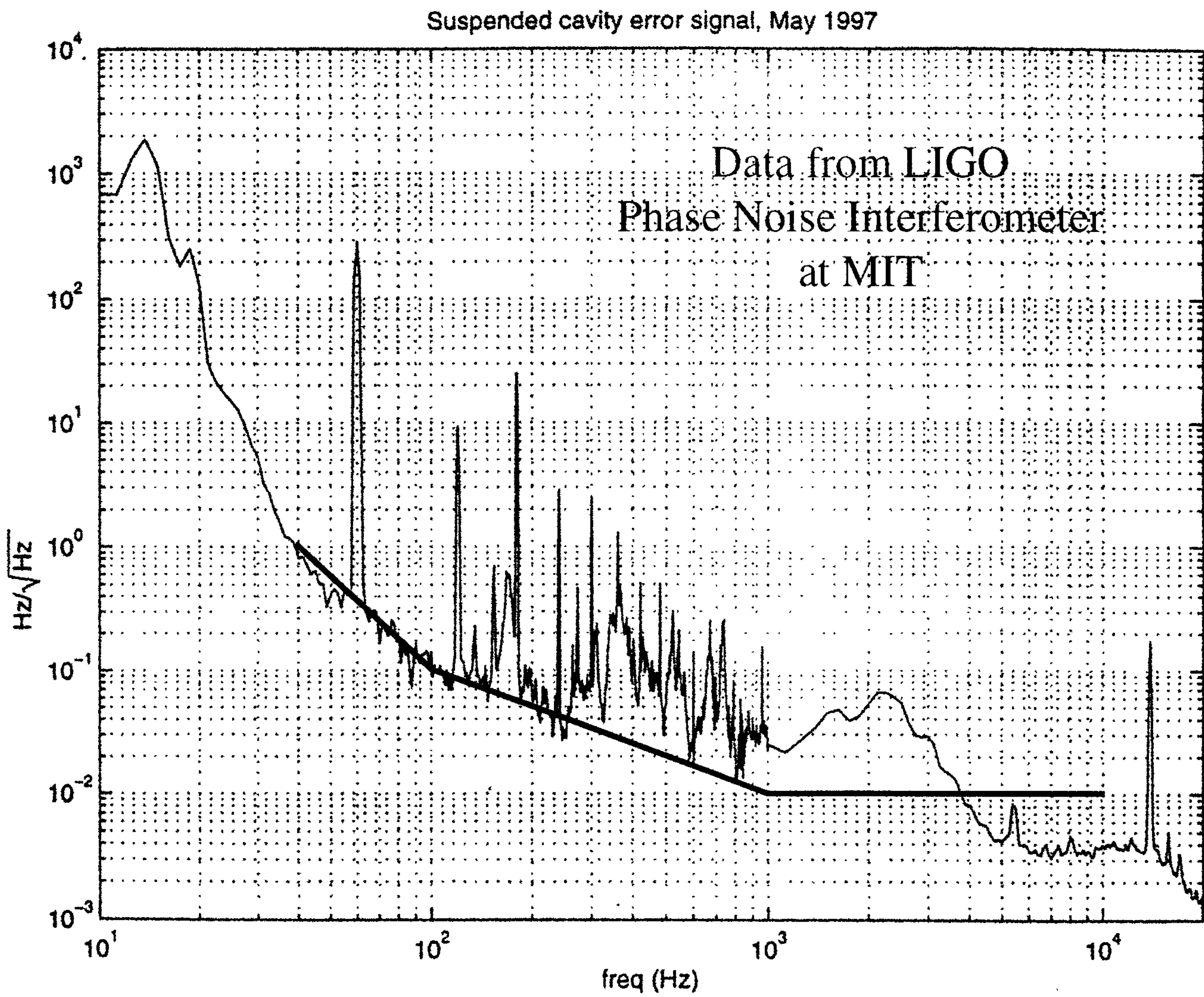
4/14/97
~rick/Yag/Documents/control_fig.id

Input

Amplifier

Actuator

# Measured Frequency Fluctuations
# NPRO Pre-Stabilized Laser Data



# Relative Power Fluctuations Above 24.5 MHz

- Noise propagation in MOPA systems

(T. Ralph, ANU and W. Tulloch, Stanford)

$$V_{PA} = H(V_{MO} + 1) - 1$$

V is the ratio of PSD of the relative power fluctuations to PSD of relative power fluctuations for a shot-noise-limited beam of the same power.

*H* is the power amplification factor.

- For $H = 20$, even for $V_{MO} = 1$, $V_{PA} = 39$.

- High -frequency power fluctuations must be attenuated.
  - ›› <u>Pre-mode-cleaner</u>

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# Relative Intensity Noise recorder

Unit under Test: **LIGHTWAVE ELECTRONICS**

LIGO #259 'Model 126 laser

Double Trace
Single Trace

**Values for HP3561A (1 Hz-100 kHz)**

| HP3561A Min Freq | HP3561A Max Freq |
|---|---|
| 4 | 4 |
| **LF Trans-Z (kΩ)** | **LF DC Photo-I, mA** |
| 0.050 | 20.00 |
| **N Averages:** | **Shot Noise Limit** |
| 100 | -167.96 |

**Values for HP8591 (10 kHz-1 GHz)**

| HP8591 Min Freq | HP8591 Max Freq | Shot Noise Limit |
|---|---|---|
| 4 | 8 | -161.94 |
| **HF Trans-Z (kΩ)** | **HF DC Photo-I, mA** | |
| 32.000 | 5.00 | |

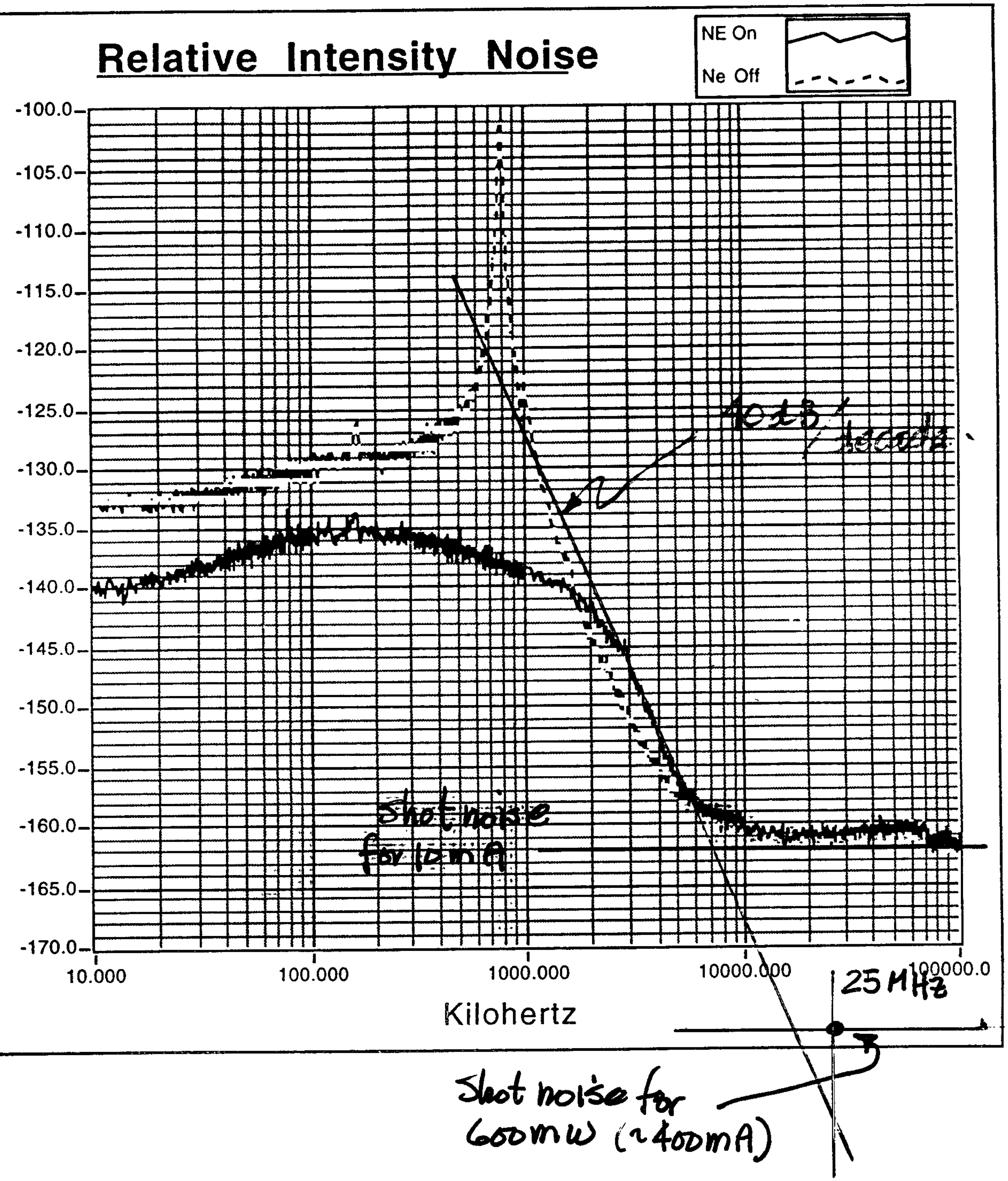
**Results**

| Freq, Hz | NE On | Ne Off |
|---|---|---|
| 1845 | | |
| 0 | | |

RMS Noise, NE On 0.02084 %

RMS Noise, NE Off 0.18543 %

## Relative Intensity Noise



The justification for this statement begins with the following expression which relates the relative power fluctuations in the output of a MOPA system to those of the maser oscillator.[1]

$$V_{MOPA} = H(V_{MO} + 1) - 1$$

Here $V_{PA}$ is the ratio of the power spectral density (PSD) of the relative power fluctuations in the power amplifier output relative to the shot noise limit for a beam of that power, $H$ is the power amplification factor, and $V_{MO}$ is the ratio of the PSD of the relative power fluctuations in the master oscillator output relative to the shot noise limit for a beam of that power. If one samples a fraction of the output of the MOPA, the PSD of relative power fluctuations in the sampled beam is given by[2]

$$V_{SAMP} = 1 + \eta(V_{MOPA} - 1)$$

Here $\eta$ is the ratio of the sampled power to the MOPA output power. Combining the two expressions above gives

$$V_{SAMP} = 1 + \eta[H(V_{MO} + 1) - 2]$$

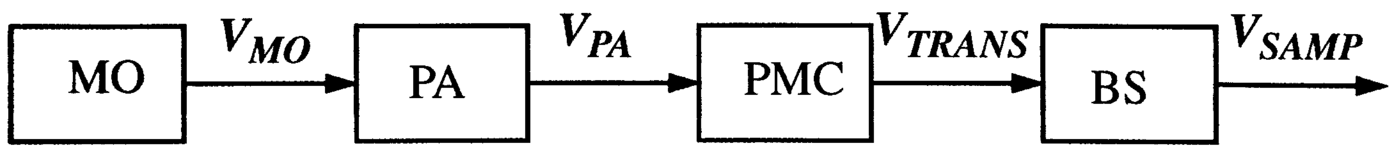
For the LIGO 10-W laser, where the master oscillator power is approximately 500 mW, and in the case where the sampled power is approximately 600 mW (the expected power at the dark port of the interferometer), $V_{SAMP} \approx V_{MO} + 2$. Thus, even if the PSD of relative power fluctuations of the master oscillator is at the shot noise limit ($V_{MO} = 1$), the PSD of the relative power fluctuations in the sampled beam will be approximately three times the shot noise limit. In order to reduce the relative power fluctuations to the required level, a passive optical filter, a pre-mode-cleaner (PMC), will be employed.

Using the vocabulary introduced by T. Ralph, the filtering of the PSD of relative power fluctuations as a function of frequency by a Fabry-Perot cavity is given by

$$V_{TRANS}(f) = \left(\frac{1}{1 + (f/f_c)^2}\right)(V_{INPUT} - 1) + 1$$

1. Private conversation with T. Ralph of Australian National University, Canberra, Australia.
2. *ibid.*

## Shot-noise-limited Power Fluctuations




- Required Pre-mode-cleaner bandwidth

$$f_c = f\left\{\frac{\eta[H(V_{MO}+1)-2]}{V_{SAMP}(f)-1} - 1\right\}^{-1/2}$$

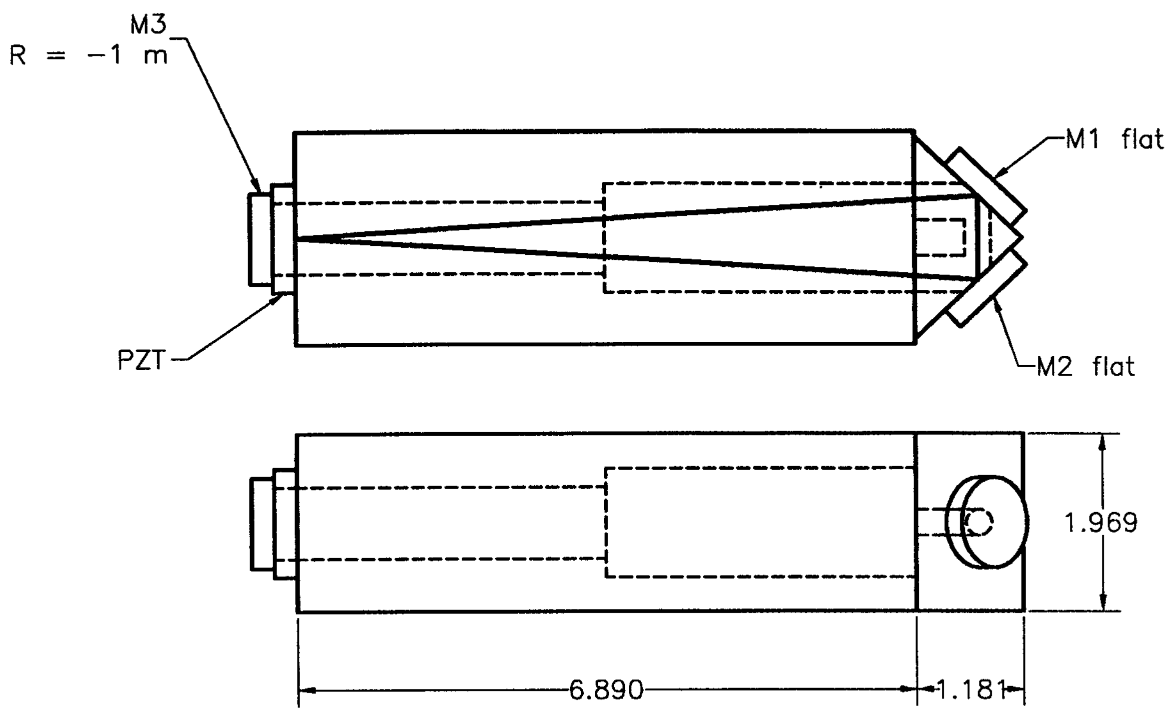
$\eta$ is the fraction of the beam sampled.

For $V_{SAMP} < 1.01, f = 24.5$ MHz, $\eta = 0.6/10$, $H = 20$ and $V_{MO} = 1$,

$$f_c < 1.63 \text{ MHz}$$

# The Pre-mode-cleaner

›› Developed in collaboration with N. Uehara, B. Willke, and E. Gustafson of Stanford University




DIMENSIONS IN INCHES
MATERIAL: FUSED SILICA

›› $f_c < 1.65$ MHz (finesse ~216)

›› Operated in air, close to LIGO circulating power (150 kW/cm$^2$)

›› Transmission efficiency > 98%

# PSL Testbed Schedule.

- pre-mode cleaner system - P. King, B. Willke 9/11/97
- frequency shifter, wide band actuator, analyzer cavity - S. Seel 11/7/97
- Alpha-1 LIGO 10-W laser - R. Savage 11/15/97
- VME-based monitor and control system - R. Abbott 12/1/97
- frequency stabilization (VME) - R. Abbott, S. Seel. 12/15/97
- laser table enclosure - L. Cardenas 1/1/98
- power stabilization - 2/1/98
- tidal actuator - S. Seel 2/15/98
- automate lock acquisition - R. Abbott, P. King 3/1/98
- PSL-external diagnostics - 3/15/98
- PSL-internal diagnostics - 4/1/98

- install final testbed laser system at WA 2k ifo
  4/6/98 - 6/12/98
  - ▲ PSL output beam to IOO - WA 2K 6/21/98

- install first "production PSL at WA 4K 1/1/99.
- install PSL at Livingston 3/1/99.