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LIGO II Pre-stabilized Laser (PSL) Conceptual Design

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LSC Lasers and Optics Working Group

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1 INTRODUCTION

1.1. Purpose

The purpose of this document is to present a conceptual design that shows that the requirements presented in *LIGO II Pre-stabilized Laser (PSL) Design Requirements*, LIGO-T000035-D are reasonable and realizable.

The principal intended audience for this document is the LIGO II Detector team.

1.2. Scope

This document details the expected challenges and a conceptual design solution generated to meet the requirements presented in *LIGO II Pre-stabilized Laser (PSL) Design Requirements*, LIGO-T000035-D.

This document provides a brief discussion of the requirements for the PSL and where these requirements come from. It gives an overview of the PSL subsystem - what is and what is not included in the PSL subsystem, its location in the LVEA, the relationship between the PSL and other LIGO II subsystems, and its features and capabilities of. Schemes to implement the frequency and power stabilization loops are presented, along with their estimated performance levels.

1.3. Document Organization

1.3.1. Acronyms

AOM	Acousto-Optic Modulator (optical hardware)
ASD	Amplitude Spectral Density
CCD	Charge Coupled Device
CDS	Control and Data System (detector subsystem)
COC	Core Optics Components (detector subsystem)
DC	Direct Current (steady state - low frequency)
EOM	Electro-Optic Modulator (optical hardware)
GW	Gravitational Wave
HWP	Half-Wave Plate (optical hardware)
IOO	Input Optics (detector subsystem, formerly named Input / Output Optics)
LIGO	Laser Interferometer Gravitational-Wave Observatory
LSC	Length Sensing / Control (detector subsystem) or LIGO Science Collaboration
LVEA	Laser and Vacuum Equipment Area (of the LIGO observatories)
MIT	Massachusetts Institute of Technology
MO	Master Oscillator
MOPA	Master-Oscillator-Power-Amplifier (laser configuration)
Nd:YAG	Neodymium doped Yttrium Aluminium Garnet (laser gain medium)
NPRO	Non-Planar Ring Oscillator (laser geometry)

PDH	Pound-Drever-Hall (reflection locking technique)
PCPC	Phase-Correcting Pockels Cell
PSD	Power Spectral Density
PSPD	Power Stabilization Photodetector
PSL	Pre-Stabilized Laser (detector subsystem)
PZT	Piezoelectric Transducer (mechanical hardware)
RF	Radio Frequency
RFAM	Radio Frequency Amplitude Modulation
RIN	Relative Intensity Noise
SEI	Seismic Isolation
TBD	To Be Determined

1.3.2. Applicable Documents

1.3.2.1 LIGO Documents

- *LIGO II Pre-stabilized Laser (PSL) Design Requirements*, LIGO-T000035-W
- *(Infrared) Pre-stabilized Laser (PSL) Design Requirements* - LIGO T970080-09-D
- *(Infrared) Pre-stabilized Laser (PSL) Conceptual Design* - LIGO T970087-04-D
- *(Infrared) Pre-stabilized Laser (PSL) Final Design* - LIGO T990025-04-D
- *LSC White Paper on Detector Research and Development*, LIGO-T990080-00-D
- *(Infrared) Pre-stabilized Laser (PSL) Electronics Design Requirements*, LIGO-T970115-00-C
- *IR PSL CDS Conceptual Design Document*, LIGO-T970114-00-C
- *Frequency Stabilization: Servo Configuration & Subsystem Interface Specification*, LIGO T970088-00-D

1.3.2.2 Non-LIGO Documents

- *Frequency stabilization of a monolithic Nd:YAG laser by controlling the power of the laser-diode pump source*, B. Willke et al., accepted for publication in Optics Letters.
- *Monolithic, unidirectional single-mode Nd:YAG ring laser*, Thomas J. Kane and Robert L. Byer, Opt. Lett., **10**, pp 65-67 (1985).

1.3.3. Definition of Terms

• Gaussian beam	A beam of electromagnetic radiation such as that often produced by lasers, in which the transverse electric field varies as $E = E_0 e^{-r^2/w^2}$, where w is the beam spot size.
• M^2 or M value	The parameter M or M^2 is a measure of the departure of a Gaussian beam from a pure TEM_{00} mode. If the mode were a pure TEM_{00} mode, then $M^2 = 1$. The beam waist-divergence product for a non-TEM_{00} mode is M^2 that of a TEM_{00} mode.
• modulation index	If the phase of the laser is represented by $\omega_0 t + \beta \sin \omega_m t$, then the amplitude of the phase modulation, β, is referred to as the modulation index.

• spot size	The characteristic size for a Gaussian laser beam, defined as the distance (radius) at which the electric field drops to $1/e$ times the maximum value, E_0 (at $r = 0$).

2 SYSTEM OVERVIEW

The PSL contains the laser source for the LIGO interferometers and is therefore situated at the beginning of the optical train. As shown in Figure 1(This figure is for the LIGO I detector. It will be updated once similar information is available for the LIGO II detector), the PSL passes the prestabilized laser radiation to **IOO** which in turn passes it to **COC**. Laser frequency correction signals are passed to the PSL from both **IOO** and **LSC**. The principal signal interface for the PSL is with **CDS**.

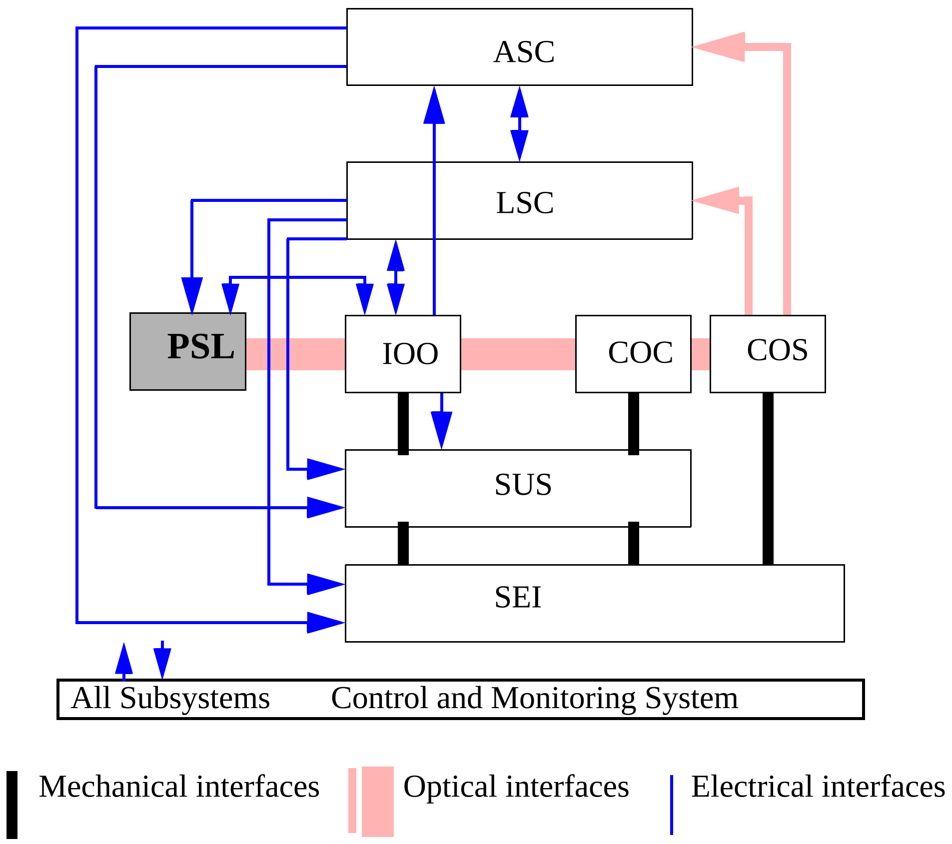

Figure 1: Block diagram showing the relationship of the PSL to other detector subsystems.

2.1. Introduction

The PSL subsystem includes the following elements:

- The LIGO II Laser with power supplies and cooling system.
- Frequency stabilization control loop utilizing a rigid reference cavity suspended in vacuum on a vibration isolation stack, electro-optic modulator for fast frequency correction, and control of master oscillator frequency fluctuations via stabilization of the current driving the pump laser diode.
- Power stabilization control loop utilizing a power stabilization photodetector located as close as possible (TBD) to the power recycling mirror, perhaps isolated against seismic motion inside the vacuum chamber.
- A deformable mirror located after the first pass of the final laser amplification stage to reduce laser output power in non-TEMoo modes.
- A triangular pre-modecleaner to attenuate power fluctuations at RF frequencies, housed in a sealed vessel to reduce atmospheric pressure-induced optical path length changes.
- Environmental control including and optical table enclosure with acoustic shielding.
- Optical table with vibration isolation system.

It does NOT include:

- Mode matching lenses or steering mirrors for the input optics.
- Electro-optics for modulation frequencies used outside the PSL subsystem.

2.2. PSL Location

Figure 2 shows the location of the each PSL and the **CDS** electronics racks for the PSLs in the LVEA at the LIGO Hanford Observatory.

Figure 2: The LIGO Hanford Observatory LVEA floor plan showing the locations of the two PSLs and the electronics racks.

Figure 3 shows the location of the PSL and the **CDS** electronics racks for the PSL in the LVEA at the LIGO Livingston Observatory.

Figure 3: The LIGO Livingston Observatory LVEA floor plan showing the PSL and electronics racks locations.

2.3. The IOO / PSL Optical Table

Figure 4 shows the partition of the **IOO** / PSL optical table between PSL and **IOO** and the coordinate system employed in describing the interface between the PSL and **IOO**.

Figure 4: Relative positions of the PSL and IOO areas on the shared PSL / IOO optical table.

2.4. Optical Layout

Figure 5 shows a schematic of the optical layout and control strategy. Note that the beam directed toward the reference cavity for frequency stabilization is split off from the main output beam

AFTER the PMC.

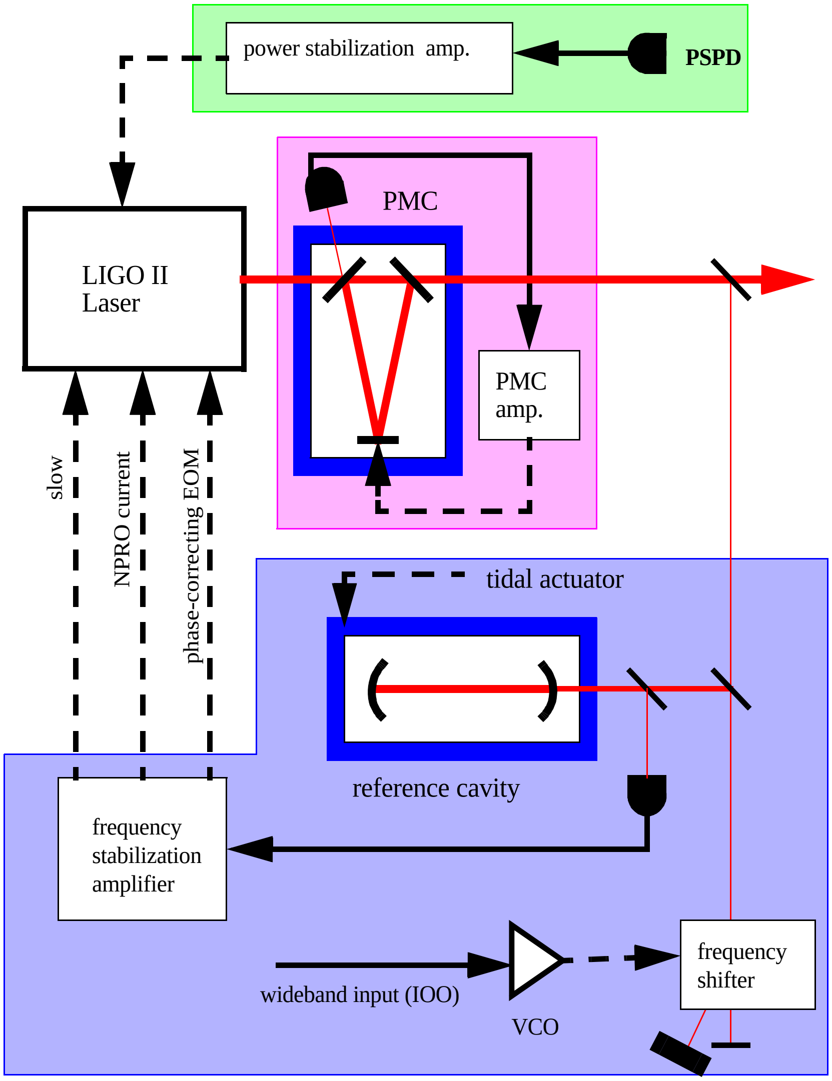

Figure 5: **PSL optical layout and control strategy**. Need to add deformable mirror to this figure.

2.5. Facilities Interfaces

The PSL will rely on the LIGO facility for the supply of the mains electrical power, temperature and humidity control, and space and utilities for the laser power supplies and chillers.

2.6. Remote Control

All PSL controls will be actuated via CDS. The performance of the PSL will be monitored continuously and logged to allow comparison with previous performance levels. The computer will also control the various steps in the lock acquisition sequence.

2.7. Features / Capabilities

The LIGO II PSL conceptual design is based on the LIGO I PSL. It incorporates the following features:

- laser frequency control via feedback to the NPRO pump diode current. This is believed to be the source of much of the NPRO frequency noise and the GEO group has been successful in suppressing frequency fluctuations using this technique[1].
- the LIGO II laser utilizes a deformable mirror to control the output beam phase front quality. This mirror is located between the 20-W first stage and the amplifiers.
- the sample of the laser output beam that is directed to the frequency reference cavity is picked off AFTER the pre-modecleaner (PMC) in order to improve beam quality and suppress frequency noise induced by the PMC due to length fluctuations. This couples the PMC and FSS loops. P. King is in the process of testing this technique using LIGO I PSL hardware at Caltech.
- the PMC is mounted inside a sealed container in order to eliminate atmospheric pressure-induced optical path length changes.
- the number of optical mounts is kept to a minimum and all mounts are extremely rigid in order to reduce frequency fluctuations induced by optical mount vibrations.
- the laser table is mounted on an active vibration isolation system to reduce the relative motion of optical components due optical table vibrations induced by seismic motion.
- the optical table enclosure is acoustically shielded in order to reduce optic motion caused by acoustic noise.
- wideband input for IOO frequency control actuator
- tidal actuator for very low frequency control of laser frequency

3 PHYSICAL IMPLEMENTATION

3.1. Physical Implementation

3.2. Optical Table Enclosure

Figure 6: The IOO / PSL shared optical table.

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[1] Frequency *stabilization of a monolithic Nd:YAG laser by controlling the power of the laser-diode pump source*, B. Willke et al., accepted for publication in Optics Letters.

3.3. Detailed Optical Layout

The PSL optical layout is given in Figure 7. The components of the optical layout are described in Table 1.

Figure 7: PSL optical layout.

Table 1: Optical layout components.

Optical Component	*Comments*	*Assumed Performance*
(example) beamsplitter	*e.g.* CVI part W2-PW1-1012-UV-1064-45S	T = 99.5%

4 THE LIGO II LASER

4.1. System Overview

The conceptual design for the LIGO II Laser is based on the premise in *LSC White Paper on Detector Research and Development*, LIGO-T990080-00-D, “The Nd:YAG pre-stabilized laser design resembles that of LIGO I, but with the addition of several stages of amplification following the present 10 W laser.” Thus, we have chosen to develop the concept of using a LIGO 10-W Laser as the front end. For reasons that will be explained in detail below, the LIGO 10-W laser (subsequently referred to at the LIGO I Laser) is modified to deliver 20-W of laser power. This capability has been demonstrated by the manufacturer, Lightwave Electronics, Inc., and we propose working with them to make operation at the 20 watt level a standard capability. A pre-mode-cleaner, similar to the LIGO I design, is placed after the 20-W front end to filter relative intensity noise and beam spatial imperfections before the amplification stages. Two amplification stages employing end-pumped, zig-zag slab amplifiers, increase the laser power to 70 watts then 180 watts. All powers quoted are in a circular TEMoo mode.

We are concerned that even if the LIGO I laser can operate at the 20 watt level and deliver the performance specified in the LIGO I Laser Target Specifications[1] (see Appendix 2), measures

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[1] The delivered LIGO I lasers typically perform below the target specifications in two important areas. The output power in non-TEM_{00} modes is typically closer to 20 percent than the specified 10 percent and, more importantly, the RIN at 25 MHz has been measured to be about 6 dB above the specification. These factors will be discussed and considered in detail in the relevant sections.

required to stabilize the amplified output to the required PSL levels will prove untenable. Substituting a 20-W injection-locked oscillator for the LIGO I Laser promises to significantly reduce the noise of the laser front end, thus simplifying the subsequent stabilization. Both because we feel that this may become necessary and because procurement of the LIGO II Laser from a commercial vendor[1] may lead to this approach, we include a description of a 20-W injection-locked oscillator in Appendix 1. Although this design will be developed only for the LIGO I Laser front end option, areas where the injection-locked oscillator might offer significant advantages over the LIGO I Laser will be noted.

Figure. Schematic of LIGO II laser showing LIGO I front end, laser pre-modecleaner, and amplification stages.

4.2. LIGO I Laser Front End (Rick)

Add detail from info. for LIGO 10-W Laser.

In this conceptual design, we utilize a LIGO I Laser modified to produce 20 watts of output power. The LIGO I Laser (typically referred to as the LIGO 10-W Laser) was originally designed to deliver 10 watts of output power. We assume that Lightwave will have developed the capabilities of the 10-W laser to deliver 20 watts with similar noise performance to the 10-W model.

Figure. Schematic of LIGO I laser

4.3. Laser pre-modecleaner

A pre-modecleaner, similar in design to that utilized after the laser in the LIGO I PSL, is positioned after the 20-W front end. This laser pre-modecleaner (LPMC) serves to reduce RIN at the GW modulation frequency, to filter the spatial mode of the beam and to define the beam parameters, spot size and location, before the final amplification stages.

4.4. Amplifier Stages (Todd and Peter)

Move deformable mirror to after second amplifier stage in the figure below.

Need straight-line estimates of free-running frequency and intensity noise in-band and predicted beam quality out of the last amplifier considering that we now have a very clean beam from the LPMC going into the amplifiers.

Please check my simple predictions of noise propagation in the amplification stages in section on RIN at 25 MHz.

The amplifier stages take the beam from 20 W to 180 W. The numbers presented here are extremely conservative with respect to the required pump power. The spec on pump power leaves

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[1] The target specifications for the LIGO II Laser that were used to solicit letters of interest from commercial vendors are included in Appendix 3.

a 30% margin to allow for degradation of the diodes over time and the slabs operate at about 20% of their stress fracture limit.

Amplification is accomplished in two stages, as shown in Figure 8 The input to each stage uses three or four mode matching lenses. The amplifiers are edge-pumped zig-zag slabs of Nd:YAG with conduction cooling and normal incidence end faces. They have an SiO2 coating on the total internal reflection faces, an AR coating at 1064 nm on the end faces and an AR coating at 808 nm on the edge faces. Two flat mirrors that are HR at 1064 are used to steer the beam in the slab and a quarter wave plate, curved HR mirror and polarizing beamsplitter are used to create a second pass that is separated by polarization.

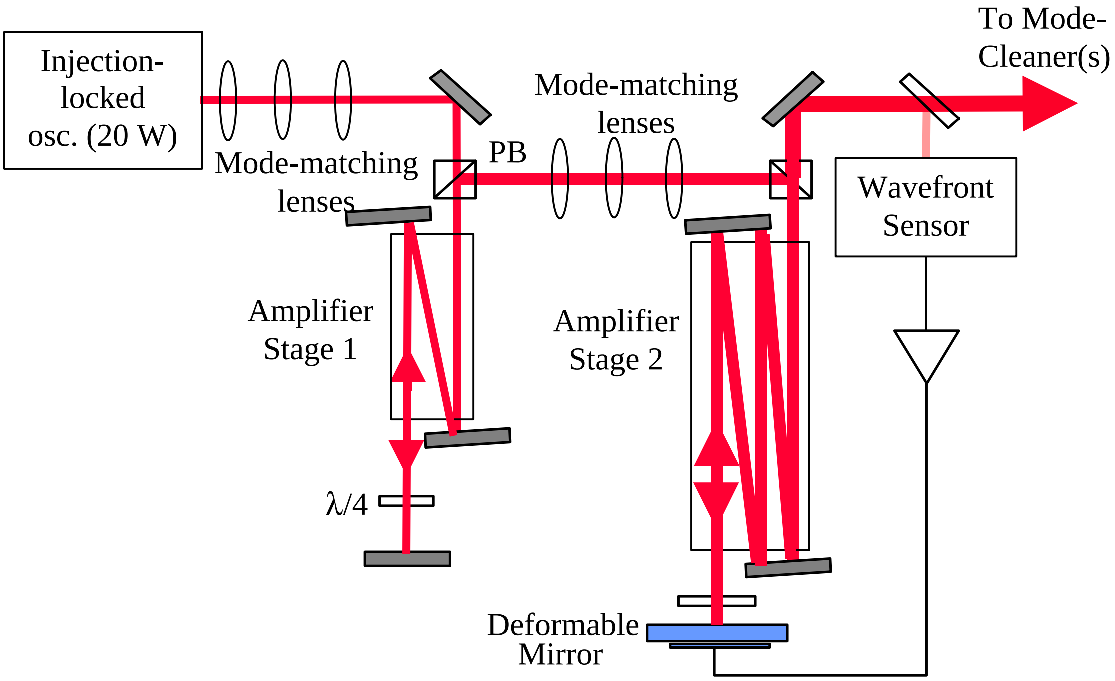

Figure 8: The optical layout of the two-stage amplifier.

The mechanical and optical parameters for the first and second amplification stages are given in Table 2 and Table 3. The back mirror for the second stage is a deformable mirror (refer to Figure 8).

Table 2: Amplifier Stage 1 Parameters

Input power	20 W
Output power	70 W
Slab dimensions:	thickness = 1.2 mm
	width = 4.4 mm
	length = 17.1 mm
End face angles	35 degrees (same as internal bounce angle).
Pump power	500 W (fiber coupled laser diodes)

Table 3: Amplifier Stage 2 Parameters

Input power	70 W
Output power	180 W
Slab dimensions:	thickness = 1.5 mm
	width = 7.3 mm
	length = 29.9 mm
End face angles	35 degrees (same as internal bounce angle).
Pump power	1000 W (fiber coupled laser diodes)

4.4.0.0.1 Estimates of output properties:

4.4.0.0.1.1 Beam Quality and Adaptive Optics:

Since the output intensity from both amplifier stages is well above the saturation intensity, no significant beam distortion is expected due to spatially varying saturation. The primary beam distortions will be due to thermal effects in the slab itself. The deformable mirror will provide correction of distortions to optimize power extraction from the final amplifier pass and to allow active mode matching to the IOO chain. Although final experimental verification of the adaptive optics system has yet to be completed, some design decisions can be made based on experience with adaptive optics and general optical design arguments.

The dominant aberrations induced on the laser when transmitting through the slab amplifiers are spherical lensing and astigmatism. There are almost certainly higher-order aberrations, but they are much smaller. Further measurement needs to be made on the laser amplifier before specifying the number of actuators on the mirror, but if only astigmatism needs correction, we have fabricated and tested some cylindrical deformable mirrors that will return the beam to a spherical wavefront with a single actuator. If higher order aberrations need compensation, two actuators will be needed on the mirror for each spatial period of the aberration.

The silicon membrane deformable mirror with high-order aberration compensation capability being developed at Stanford currently uses a 3 mm spacing between actuators. (This is not a fundamental limit of the architecture, but will serve as a design point for this document.) Since the LIGO laser beam in the laser amplifier is going to be roughly 1 mm in diameter, a beam-expanding telescope will be required to fit the laser onto the deformable mirror. Further, the mirrors being fabricated at Stanford are being coated for reflectivity with gold. (This is not the only coating choice available, but a low-stress dielectric coating has not been applied due to financial constraints.) However, even with the relatively lossy gold coating these mirrors can withstand 10 W of 1064 nm light focussed to a <1 mm spot.

The adaptive optics system design is based on the current wavefront measurement data, the current state of the deformable mirror technology at Stanford, and a guess at the important aberrations of the system. The mirror will be placed between first and second passes of the final amplifier. A fallback plan is to place it before the first amplifier if power handling becomes an issue (this is not preferable because it complicates the feedback control. A beam-expanding telescope is used to match the beam to the size of the mirror. The mirror will need approximately 25 actuators to compensate for low-order aberrations. (Such a mirror can be purchased now from OKO technologies if the aberrations are very small.) Finally a Hartmann-type wavefront sensor will be used to measure the wavefront after the amplifier. A dielectric plate near Brewster's angle would be best for sampling the beam for the wavefront sensor. The wavefront sensor will need at least one aperture for every actuator, but over sampling is preferred to avoid alignment and waffle-mode problems.

With a complex optical system like this amplifier chain, the M2 metric fails to give a thorough characterization. Using RMS wavefront error from spherical gives more precise information. This metric does not give any spatial frequency information though, so decomposing the wavefront into Zernike polynomials or the laser into its Hermite-Gaussian modes may be needed. We expect that the RMS wavefront error will be able to be reduced to roughly the measurement noise of the wavefront sensor, which is typically a few nanometers or roughly l/300.

4.4.0.0.1.2 RMS power noise:

The Stanford testbed typically operates with 10-3 rms power noise in open loop and we expect similar performance for the proposed system. We believe that this is mainly due to fluctuations in the pump power. Thus some low frequency control will be required.

4.4.0.0.1.3 RF power noise:

The amplifier gain has a total power gain of 180/20=9, so the output beam will be about 1+2*(G-1)=17 times above the shot noise limit for the full output power (assuming that the 20W input is at the SNL (NOTE: Section 1 states that the noise is expected to be significantly higher than this, 1.01 times the relative shot noise for 5 W of light. We need to revise this estimate.). Since we need to be 1.005 times the SNL at 5 W and 25 MHz, a mode cleaner with a corner frequency of about 300 kHz is required. For a 100 MHz modulation frequency, the corner frequency improves to 1.2 MHz.

4.4.0.0.1.4 Frequency Noise:

The amplifiers will add some small phase noise at 100 Hz due to temperature fluctuations and ASE. Calculations show that these effects are not significant but measurements on the testbed system are needed to confirm this.

4.4.1. Features

4.5. Specifications

The LIGO project has solicited letters of intent from commercial companies who may have an interest in designing and fabricating the LIGO II laser. For this solicitation, a list of target specifications was generated[1]. This list is reproduced in Appendix 3. A summary of the target specifications for the LIGO II laser is provided in Table 4.

Table 4: LIGO II laser target specifications summary.

Parameter	*Specification*
1. type of laser	Nd^{3+}:YAG
2. wavelength	1064 nm
3. power in circular TEM_{00} mode	> 180 W
4. power in all other modes	< 36 W
5. polarization extinction ratio	> 500:1 in the vertical plane
6. relative power fluctuations	$< 10^{-5}$ /$Hz^{1/2}$ between 100 Hz and 10 kHz $< 10^{-6}$ /$Hz^{1/2}$ between 10 kHz and 3 MHz $< 1.8 \times 10^{-9}$ /$Hz^{1/2}$ above 25 MHz (2 times shot noise limit for 100 mA of photodetected current)
7. frequency fluctuations	$< 2 \times 10^{3}$ Hz/$Hz^{1/2}$ at 100 Hz $< 2 \times 10^{2}$ Hz/$Hz^{1/2}$ at 1 kHz
8. reliability: *i*. mean time between failure (MTBF) *ii*. minimum time between required beam alignment adjustment	 > 10 000 hours > 500 hours

The predicted performance of the LIGO II Laser in this conceptual design differs from the LIGO II Laser target specifications as follows:

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[1] Nd:YAG Target Specifications, LIGO-C000060-00-D.

- the power in non-TEM$_{00}$ modes is ?? (Todd and Peter) for the concept laser. Significantly lower than the 36 watts in the target specifications.
- the RIN at 25 MHz for a 100 mA sample of the 180 watt output of the concept laser is predicted to be about .09 dB above the shot noise for 100 mA. This as about a factor of 140 below the 6 dB level given in the target specifications. The conceptual design would have to be significantly modifies if the LIGO II laser were to be as noisy as the target specification allows.

5 FREQUENCY STABILIZATION

5.1. Overview

This scheme follows the strategy utilized for the LIGO I detectors. The frequency stabilization scheme employs nested loops utilizing the increasing frequency sensitivity of three Fabry-Perot cavities; the PSL reference cavity, the **IOO** mode-cleaner, and the interferometer’s 4-km-long arm cavities using the **LSC** common-mode signal.

Figure 9: PSL Frequency Control Concept.

5.2. PSL Frequency Stabilization Requirements (Benno and Rick)

5.2.1. Free-running Frequency Noise (from Todd and Peter)

5.2.2. Required Control Loop Performance (Rick)

5.3. Frequency Fluctuation Sensor (Benno)

5.3.1. Reference Cavity (Benno)

5.3.1.1 Suspension and vibration isolation system (Benno and Rick with help from Gian-

carlo Cella)

5.3.2. Pound-Drever-Hall Locking (Benno)

5.3.2.1 Reference cavity RF photodetector (Rick)

Use recent LIGO I design.

5.3.2.2 PDH parameters (Benno)

5.4. Frequency Control Loop Actuators (Benno and Rick)

5.4.1. NPRO temperature control - SLOW actuator (Rick)

5.4.2. NPRO pump diode current control - PDC actuator (Benno)

5.4.3. Phase-correcting EOM actuator (Benno)

5.5. Frequency Stabilization Servo Amplifier (Benno and Rick)

5.6. Frequency Control Loop Performance Estimates (Benno and Rick)

6 EXTERNAL FREQUENCY CONTROL

6.1. Wideband Actuator (David)

6.1.1. Requirements (David)

6.1.2. AOM Frequency Shifter (Rick)

6.1.3. VCO (David and Rick)

6.2. Tidal Actuator (Rick)

6.2.1. Requirements (Rick)

6.2.2. Reference Cavity Temperature Stabilization and Control (Rick)

7 POWER STABILIZATION (DAVID)

7.1. Low Frequency Power Variations (David, Peter, and Todd)

7.2. Fractional Light Power Fluctuations in the GW Band (David)

7.2.1. Performance Requirements (David)

7.2.2. Free-running Relative Power Fluctuations (Peter and Todd)

7.2.3. Required Control Loop Performance (David)

7.2.4. Power Stabilization Photodetector (David)

7.2.4.1 Location (David and Benno)

7.2.5. Power Actuators (Peter and Todd)

7.2.5.1 DC Power Adjust Actuator (Peter and Todd)

7.2.5.2 Current Shunt Actuator (Peter and Todd)

7.2.6. Power Stabilization Control Loop Amplifier (David)

7.2.7. Power Stabilization Control Loop Performance Estimate (David)

7.3. Shot-noise-limited Power Fluctuations at GW Modulation Frequency (Rick and David)

7.3.1. Performance requirements

The amplitude spectral density of the relative power fluctuations (RIN) at the gravitational wave detection modulation frequency, 25 MHz, is required to be less than 1.005 times the shot noise limit for 5 watts of laser power at the output of the PSL.

7.3.2. Free-running noise estimate

Estimation of the RIN at 25 MHz starts with measurements of the as-built performance of LIGO I lasers operating at 10-W output power and uses the formalism adopted during the LIGO I PSL conceptual design and described in Appendix 3, Noise Propagation in MOPA Systems, of *(Infrared) Pre-stabilized Laser (PSL) Conceptual Design*, LIGO T970087-04-D to estimate the effect of amplification. As shown in Appendix 4 the PSD of the RIN at 25 MHz for the LIGO 10-W Laser has been measured to be about 137 times the shot noise for a 10 watt beam. In order to estimate the expected noise if the output of the LIGO 10-W Laser were increased to 20 watts, we apply the MOPA amplification formula

$$,V_{20} = H(V_{10} + 1) - 1\,, \tag{1}$$

here H is the amplification factor, 2 in this case. Thus for the 20 watt output, we estimate that V_{20} will be about 275. For a 147 mW (100 mA) sample of this beam, using the formula which would yield about 100 mA of current, the V factor, $V_{0.1}$, would be about 3.015.

If we were to amplify the 20 watt output of the laser front end up to the 180 watt level, we would obtain, by applying Equation (1), $V_{180} = 2467$. The LIGO II PSL requirement for the PSD of the RIN at 25 MHz is less than 1.01 times the shot noise for 5 watts of laser power, or $V_5 \leq 1.01$. The noise for a 5 watt sample of a 20 watt beam is given by

$$V_{sample} = 1 + \eta(V_{main} - 1) \tag{2}$$

where η, the ratio of the sampled beam power to the main beam power, is 1/4. This yields $V_5 = 69.5$. If we were to try to meet the LIGO II requirement by filtering with a pre-mode-cleaner located after the LIGO II laser, in the 180 watt output beam, the required half resonance of the PMC would be given by

$$V_{trans}(f) = \left(\frac{1}{1 + (f/f_c)^2}\right)(V_{input} - 1) = 1.01 \tag{3}$$

where f_c is the PMC half bandwidth, the frequency of interest, f, is 25 MHz and $V_{input} = 69.5$. This expression yields $f_c \cong 300MHz$. If the PMC design were similar to the LIGO I PMC, with a free spectral range of about 750 MHz, the required finesse for the LIGO II PMC would be about 1250. This is about 5.5 times the finesse of the LIGO I PMC and the input power is 18 times the LIGO I power. The circulating power would therefore be about 100 times higher than in LIGO I. The spot size on the flat mirrors in the LIGO I PMC is about 0.23 mm. Thus the power density on the flat mirrors would be about 135 MW/cm^2.

Because the required PMC finesse is so high if the LIGO I laser output is amplified without filtering before the amplification stages, a PMC similar in design to the LIGO I PMC is placed between the 20-watt front end and the amplification stages. This PMC located inside the LIGO II laser will henceforth be referred to as the laser pre-modecleaner or LPMC. In this configuration, the circulating power in the LMPC is only twice the circulating power in the LIGO I PMC[1]. The half bandwidth of the LIGO I PMC is about 1.6 MHz. Applying Equation (3) with $V_{input} = V_{20} = 275$, as described above for the expected noise of the LIGO I laser at 20 watts output power and $f_c = 1.6MHz$, yields $V_{trans_{20}} = 2.118$. If this beam were then amplified to 180 watts, the noise predicted by Equation (1) would be given by $V_{180} \cong 27.1$. For this beam, the noise at 5 watts is given by $V_5 \cong 1.724$. Applying Equation (3) the required half bandwidth for a

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[1] The LIGO I PMC has been operated for short periods with 10 watts of input power in the high-finesse mode where the finesse is about 4000 instead of the normal low- finesse value of about 225. No adverse effects of the higher circulating power were observed.

PMC placed after the LIGO II laser would be $f_c = 3.0MHz$. This is about half the finesse of the LIGO I PSL. The circulating power would still be about ten times higher than in the LIGO I PMC. The LIGO II conceptual design thus contains two resonant cavities similar to the LIGO I PMC, the LPMC located between the laser front end and the amplifiers and the LIGO II PMC located at the output of the LIGO II laser. With the cavity dimensions and mirror radii of curvature the same as the LIGO I PSL, the circulating power in the LPMC and LIGO II PMC are about 2 times and 10 times the LIGO I PSL levels, respectively.[1] The LPMC has the additional benefit of improving the spatial quality of the beam sent to the amplifiers as will be discussed in Section 4.4.

Note that this design can likely be improved by adjusting the finesse of the LPMC and the PMC to result in approximately equal circulating powers in the two resonant cavities.

7.3.3. Pre-modecleaner design (Rick)

7.3.4. PMC Length Control Loop (Rick)

7.3.5. PMC-induced Frequency Noise Estimate (Rick and David)

7.3.6. Expected Performance of the LIGO II Laser (Rick and David)

8 POWER BUDGET (RICK AND DAVID)

9 LOCK ACQUISITION

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[1] If we were to utilize a 20-W injection-locked laser front end rather than the LIGO I laser (refer to Appendix 1), the LPMC could be eliminated (from the standpoint of RIN at 25 MHz) and the required LIGO II PMC half bandwidth would be about 3.7 MHz, slightly lower finesse than that required for the LIGO I laser front end.

10 DIAGNOSTIC MODES

11 COMPUTER CONTROL INTERFACE

12 RELIABILITY AND MAINTENANCE

12.1. System-level Requirements

The PSL is required to operate continuously, without loss of ‘lock’ (even for short times), for 40 hours during normal seismic conditions (90% percentile **TBD** for either site).

APPENDIX 1 20-W INJECTION-LOCKED OSCILLATOR (PETER)

The optical layout of the 20-W injection-locked laser is shown in Figure 1. The output of a monolithic NPRO laser is amplified using a diode-pumped, injection-locked, 20-W, ring slave laser. Long term injection locking is accomplished using a Pound-Drever-Hall-like servo control that actively controls the frequency of the slave mode to be within 10% of the center of the injection locking range. The frequency of the slave is adjusted by applying a voltage to two PZT actuators on which the mirrors are mounted. One PZT has a large range and the other has a wide actuation bandwidth. Note that the Faraday isolator must be able to handle 20 W of laser power while the electro-optic modulator is only exposed to 1 W of laser power.

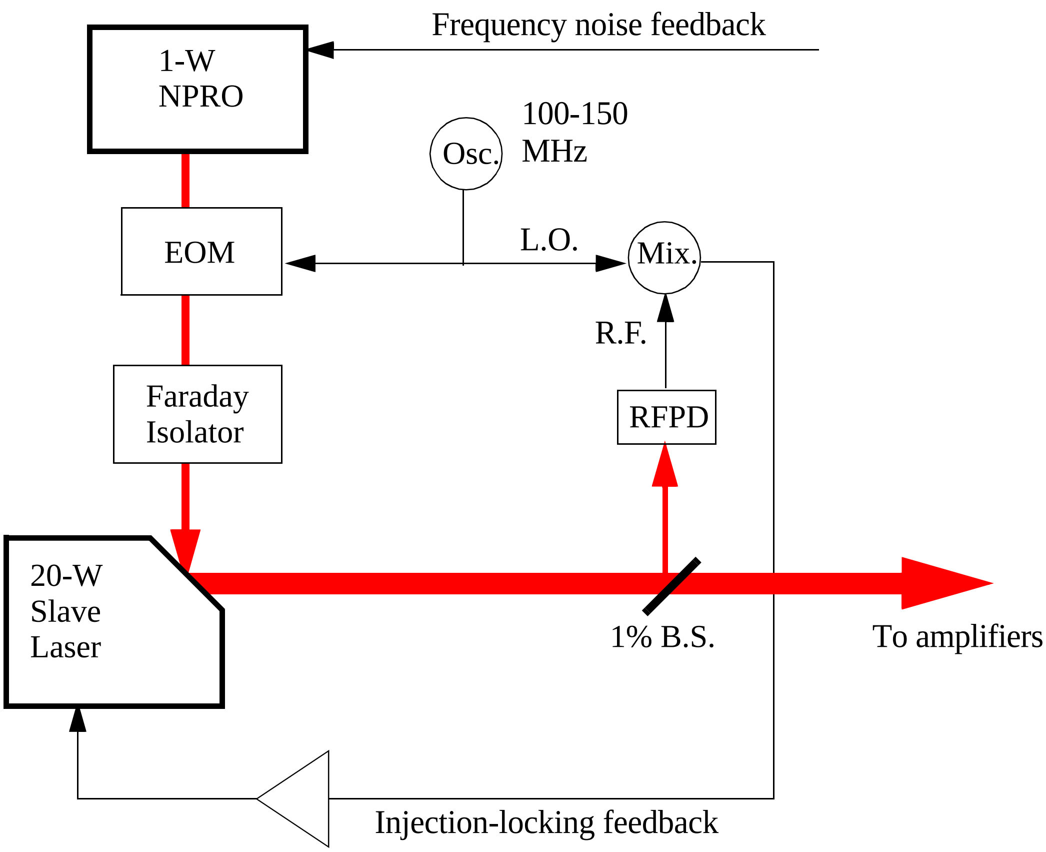

Figure 1: Optical layout of the 20-W injection-locked laser.

The output of the slave laser is expected to be an almost-diffraction-limited TEMoo mode (M^2 <1.2). The frequency noise in the GW band will be almost identical to that of the NPRO master oscillator. The relative intensity noise (RIN) will be approximately $1\times10^{-5}\ Hz/\sqrt{Hz}$ at 100 Hz. If necessary, this noise could be further reduced to less than $1\times10^{-6}\ Hz/\sqrt{Hz}$ at 100 Hz by feedback to the current of the pump diodes of the slave laser. The RIN at 25 MHz is expected to be less than 1.01 times the shot noise for 5 W of detected power.

APPENDIX 2 TARGET SPECIFICATIONS: LIGO 10-W LASER

Performance Specifications

Parameter	*Specification*
1Power in circular TEM_{00} mode	> 10 W
2. Total power in all non-TEM_{00} modes	< 1 W ($M_{horizontal} \times M_{vertical} < 1.1$)
3. Relative spot size fluctuations, $\delta w / w$	< 2% peak-to-peak
Relative Power Fluctuations, $\delta P(f) / P$:	
4. Drift over 24 hours	< 1% peak-to-peak
5. Drift over 500 hours	< 3% peak-to-peak
6. 1-100 Hz	< [-100 + 40 log(100 Hz / f)] dB / Hz
7. 100 Hz - 10 kHz	< -100 dB / Hz
8. 10 kHz - 3 MHz	< -120 dB / Hz
9. 10 MHz	< - 163 dB / Hz (within 2 dB of the shot noise limit for 10 mA photodetected current)
Relative Power Fluctuations, $\delta P(f) / P$, at 60 Hz Line Frequency and Harmonics:	
10. 60 Hz and 120 Hz	< 1 x 10^{-5} rms
11. Between 150 Hz and 10 kHz	< 1 x 10^{-5} rms
12. Between 10 kHz and 3 MHz	< 2.4 x 10^{-6} rms
13. Relative power fluctuations, $\delta P(f) / P$, at Model 126 power supply switching frequency (~80 kHz) and power amplifier power supply switching frequency	< 2 x 10^{-5} rms

Parameter	*Specification*
Frequency Fluctuations:	
14. Between 40 Hz and 100 Hz	$< [54 + 50\ \log(100\ \mathrm{Hz}/f)]$ dB Hz^2 /Hz
15. Between 100 Hz and 10 kHz	$< [54 + 20\ \log(100\ \mathrm{Hz}/f)]$ dB Hz^2 /Hz
Frequency Drift:	
16. At constant ambient temperature	< 50 MHz / hour
17. At constant ambient temperature	< 1 GHz / month
18. Per degree ambient temperature change	< 30 MHz
Frequency-to-Intensity Conversion:	
19. Fractional power change (W/W) per Hz of frequency change	< 2 x 10^{-10}
Relative Pointing Angle Fluctuations, $\delta\theta/(\theta_d/2)$, (divergence half angle, $\theta_d/2 = \lambda/(\pi \times w_0)$):	
20. Drift over 24 hours	< 2.5 x 10^{-2} peak-to-peak
21. 40 Hz to 150 Hz	< [-110 + 40 log(150 Hz / f)] dB / Hz
22. > 150 Hz	< -110 dB / Hz
Relative Transverse Position Fluctuations, $\delta x/w$, (w is the spot size):	
23. Drift over 24 hours	< 2.5 x 10^{-2} peak-to-peak
24. 40 Hz to 150 Hz	< [-110 + 40 log(150 Hz / f)] dB / Hz
25. > 150 Hz	< -110 dB / Hz

Parameter	*Specification*
26. Polarization extinction ratio	> 300:1
27. Electromagnetic interference (EMI) emissions	In compliance with CE mark, EN 55011 Class A
Reliability:	
28. Mean time between failure (MTBF)	> 10,000 hours
29. Minimum time between required beam alignment adjustments	> 2,500 hours

Configuration Specifications

Parameter	*Specification*
30. Type of laser	Nd^{3+}:YAG
31. Wavelength	1064 nm
32. Optical scheme	Master Oscillator Power Amplifier, double-pass
33. Amplifier pumping	8 x 20-W diode bar, direct-coupled, side-pumped
Frequency Control:	
34. Thermal tuning range, continuous	10 GHz
35. Thermal tuning range, total	30 GHz
36. Thermal tuning rate	1 GHz/sec
37. Piezo tuning range, ±15 V	30 MHz
38. Piezo response bandwidth, small-signal	> 30 kHz
39. Warm-up time	< 1 hour

Parameter	*Specification*
Laser head, mechanical:	
40. Support structure	2 ft. x 2 ft., 1/4 in.-20 tapped holes on 1 in. square grid
41. Modules/components	a. Model 126-1064-700 master oscillator b. Power amplifier, sealed c. Coupling and beam control optics
42. Beam height above support structure	**TBD** ±0.05 in.
43. Cover	Removable dust protective cover, metal
44. Total laser height	< 1 ft.
45. Distance from laser head to power supplies	Up to 50 ft.
Laser head, optical:	
46. Output beam waist spot size, w_0	0.25 mm **TBD** ±0.1 mm
47. Output beam waist location	**TBD** ±50 mm from output aperture

Parameter	*Specification*
Laser chiller:	
48. Type	Low-temperature, bath circulator
49. Manufacturer, Model	Neslab, RTE-140M
50. Cooling capacity	600 W at 10 °C, at ambient temp. of 20 °C
51. Pumping capacity	0.9 gpm through 100 ft. length of 3/8 in. ID hose
52. Dimensions (h x w x d)	66.0 cm x 31.4 cm x 48.3 cm (> 12 in. clearance at front and rear for ventilation)
53. Distance from laser head to chiller	Up to 50 ft.
54. Distance from chiller microprocessor controller to chiller	Up to 50 ft.
55. Laser safety	In compliance with federal register 21 CFR 1040.10 & 1040.11 laser safety standard
56. Transportability	Transportable by commercial carrier without performance degradation

Electronics Specifications

Refer to *Specification for LIGO 10W Laser Amplifier Electronics*, Lightwave Electronics document number D-0226X2.DOC, attached.

APPENDIX 3 LIGO II LASER TARGET SPECIFICATIONS (FROM LIGO-C000060-00-D)

The LIGO project is in the process of identifying commercial vendors who may be able to manufacture the LIGO II laser. As part of the source identification process, the following target specifications have been generated.

1 TYPE OF LASER

180 W, single frequency Nd:YAG solid state laser.

2 LASER LIGHT

2.1. General Properties

1. Wavelength: λ=1064 nm, single frequency

2. True CW.

3. Output Power: > 180 W in a circular TEM_{00} mode, <36 W in the sum of all non TEM_{00} modes

4. Polarization: linear, within 1 degree of vertical, extinction ration >500:1

2.2. Stability

1. Warm-up time < 2 hour. The following specifications (2-5) refer to the laser after warm-up.

2. Power: long-term variation < 1% over 24 hours

3. Frequency drift: < 100 MHz per degree C of ambient temperature change, and < 100 MHz per hour at constant ambient temperature.

4. Pointing drift (relative to divergence angle): < 2% peak-to-peak per degree C of ambient temperature change, and < 2% peak-to-peak at constant ambient temperature over 24 hours.

5. Beam diameter stability: < 2% peak-to-peak per degree C of ambient temperature change, and < 2% peak-to-peak at constant ambient temperature over 24 hours.

2.3. Noise

1. Relative power fluctuations

- Less than 10^{-5} rms at 60 Hz, 120 Hz, and 180 Hz line frequency and harmonics
- Less than $10^{-5}/\mathrm{Hz}^{1/2}$ between 100 Hz and 10 kHz
- Less than $10^{-6}/\mathrm{Hz}^{1/2}$ between 10 kHz and 3 MHz
- Within 6 dB of shot noise limit (at 100 mA photodetected current) above 25 MHz
- Relaxation oscillation: critically damped or overdamped

2. Frequency fluctuations: $<5\times10^{2}$ Hz/$\mathrm{Hz}^{1/2}$ at 100 Hz, $<5\times10^{1}$ Hz/$\mathrm{Hz}^{1/2}$ at 1 kHz

3 OUTPUT CONTROL

1. Frequency control:

- Continuously tunable over >2 GHz range, within one minute
- Continuously tunable over >10 MHz range, with a bandwidth of at least 30 kHz

2. Power control:

- Continuously tunable over 160 - 180 W
- Continuously tunable over +/- 5 W, with a bandwidth of at least 30 kHz

4 INTERFACES

4.1. Electrical

1. Maximum electrical power required: 15 kW/laser

2. Controls, outputs and inputs:

The laser and associated components shall be designed such that the unit can be operated locally or remotely via a remote control interface. The following inputs and outputs shall be included:

1. Laser on/off and standby control and status monitor
2. Laser shutter control and status monitor
3. Local/Remote control switch and monitor. Local control shall be the default mode of operation.
4. Laser frequency control as specified in section 3.1
5. Laser output power control as specified in section 3.2
6. Laser head temperature indicator
7. Laser pump diode current and voltage monitor
8. Reliable and redundant safety interlock

Acceptable types of remote interface signals include:

1. Analog voltage levels for reference and feedback: 0-10V, +/-5 V, +/-10 V
2. Binary voltage levels for status and state control: TTL
3. Contact closure for status and state control: rated 24 VDC, 1A min.
4. Other signals or types of interfaces shall be approved by LIGO prior to implementation.

3. Connectors:

All connectors shall be commercially available items that can be obtained from multiple sources. In the event that this is not possible or feasible, the vendor shall provide the connector and its mate with the unit.

4.2. Mechanical

1. The laser beam and the laser support points will be referenced to a rigid mechanical structure.
2. Support points for lifting and other handling will be provided.
3. If the laser subsystem is composed of more than one component (e.g., cooling unit/power supply/laser head), any cabling or other connections between the laser head and other components shall be at least 5m in length.
4. The laser head and any other components placed on the optics bench shall occupy an envelope no greater than 1 m(W) x 1 m(L) x 0.5 m (H)

4.3. Cooling

1. Cooling capacity and type (air, water) to be determined by the vendor.
2. The laser cooling unit will be separated from the laser head.
3. The cooling unit will be self-contained and operated on 110 V power.

5 RELIABILITY AND MAINTENANCE

1. Minimum stretch of continuous operation, between required maintenance events: 500 hours.
2. MTBF: > 10,000 hours.
3. Laser subsystems that need periodic maintenance will be designed as modules, kinematically attached to the frame whenever needed, and easy to access, remove and replace.
4. Design for easy maintainability, by technical personnel with average training level in operating and maintaining lasers.

6 SAFETY

1. The laser design shall incorporate the following additional safety features in compliance with ANSI Z136.1-1993:
    1. Protective housing
    2. Interlocks on protective housing
    3. Service access panel
    4. Key control
    5. Activation warning systems
    6. Labels

2. All control inputs shall be internally protected against overload damage.

3. Recommend optimum protective eyewear and provide information on other potential hazards of this laser design.

4. Provide instructions for safe operation of this laser system.

7 TRANSPORTABILITY

The laser should be transportable by commercial carrier without degradation in performance. Special shipping containers necessary to comply with this requirement as well as shipping and handling instructions shall be provided by the laser manufacturer.

APPENDIX 4 LIGO 10-W LASER AND PSL RIN AT 25 MHZ (RICK)

Based on measurements of the intensity noise at 25 MHz both before and after the pre-modecleaner in a LIGO I PSL prototype, we estimate the RIN at the output of the LIGO 10-W laser. The intensity noise at 25 MHz was measured by P. King and B. Willke using the prototype PSL in the Lauritsen Lab[1] at Caltech, by P. Csatorday[2] using the 2k PSL at the LIGO Hanford Observatory and by J. Kovalik[3] at the LIGO Livingston Observatory.

King and Willke measured the intensity noise between 20 MHz and 30 MHz at photocurrents of 50 mA and 100 mA both before and after a LIGO I-style pre-modecleaner (PMC) designed to reduce intensity noise. From the 50 and 100 mA measurements made after the PMC, they concluded that the light after the PMC is shot noise limited at 25 MHz for more than 50 mA of photocurrent. It is typical for researchers who observe noise levels close to the shot noise limit to conclude that the light is “shot noise limited.” However, the LIGO I design specifications required that the ASD of the RIN be less than 1.005 times the shot noise for 600 mW of light. Assuming a quantum efficiency of 0.68, this corresponds to 408 mA photodetected current. The corresponding requirement for 100 mA of photocurrent would be less than 1.00125 times the shot noise for 100 mA. Thus, in order to conclude that the light were “shot noise limited” at the level required for LIGO, one would have to be able to resolve small differences (a part in one thousand) from shot noise levels. If one were to use the technique of measuring at 100 mA and 50 mA of photocurrent and looking to see if the ratio of the measurements is 3 dB as would be expected for pure shot noise, a beam that would just meet the LIGO I requirements would yield a ratio of 3.016 dB. Measurement of a beam that exceeded the LIGO I specification by a factor of two (in PSD) would yield a ratio of 3.021 dB. Thus, a resolution of 5 mdB would be required to determine if the ASD of the RIN is within a factor of 1.4 of the specification. While this factor of two technique cannot easily verify that the PMC output beam meets the PSL specification, this same technique applied to the light incident on the PMC can yield useful information about the 10-W laser output beam noise levels.

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[1] The measured data that conclusions drawn upon them are discussed in Section 8.2 of *(Infrared Pre-stabilized Laser (PSL) Final Design*, LIGO T990025-00-D.

[2] P. Csatorday, unpublished report, *Hanford 2k PSL Intensity Noise*, circa January, 1999.

[3] Private communication with J. Kovalik, May, 2000. Report forthcoming.

The ratio of intensity noise at 100 mA to shot noise at 100 mA versus ratio of intensity noise for 100 mA to intensity noise for 50 mA is shown in Figure 1 . The data for the measurement of the

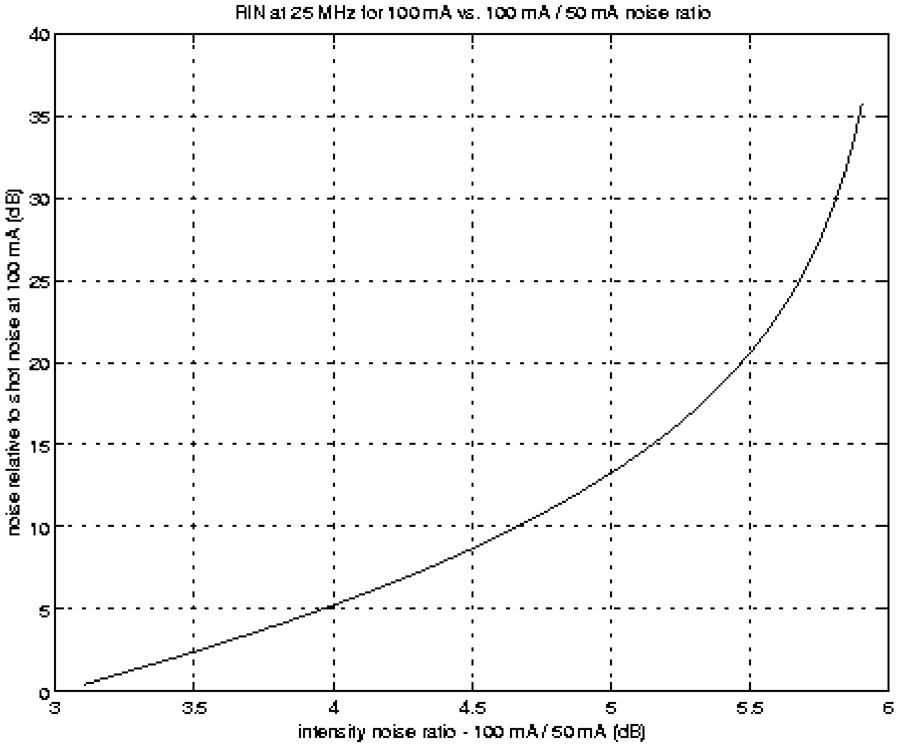

Figure 1: Ratio of beam intensity noise level to shot noise versus ratio of intensity noise at 100 mA to that at 50 mA.

intensity noise at the input to the PMC for 100 mA and 50 mA photocurrent is shown in Figure 2.

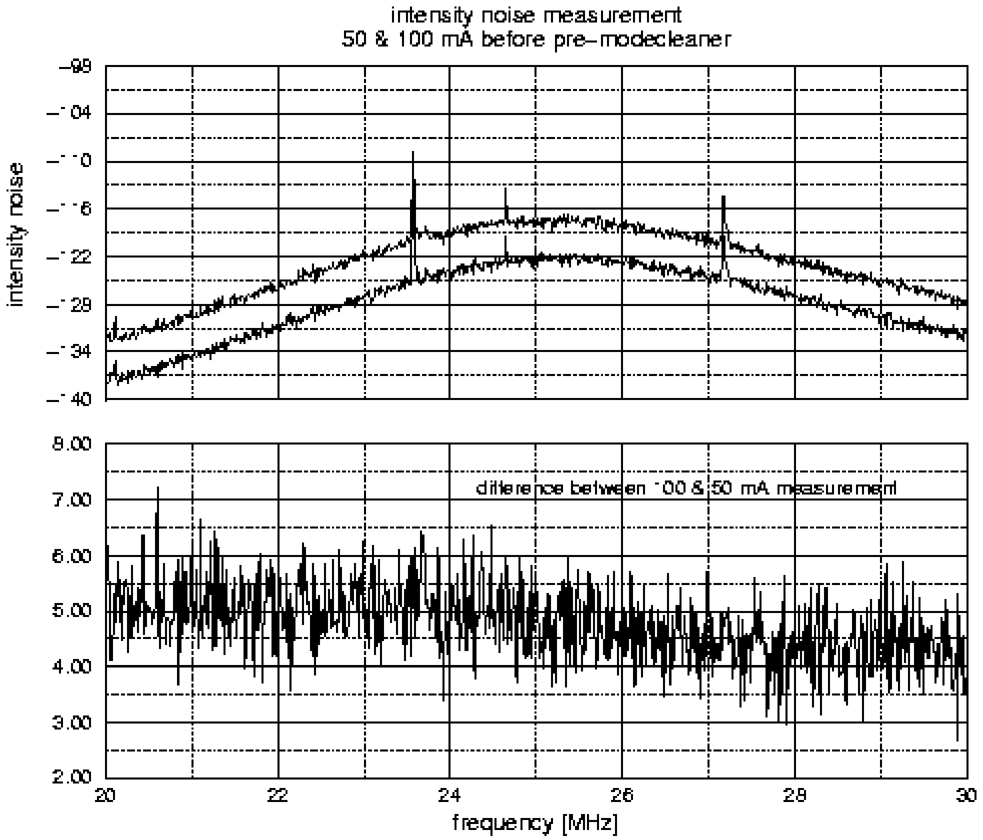

Figure 2: Measured intensity noise before the PMC in the PSL prototype at Caltech.

The ratio of the 100 mA to the 50 mA noise levels is shown in lower subplot. At 20 MHz, this ration is between 4.5 and 5 dB. As can be seen in Figure 1, this corresponds to a 100 mA noise level (ASD) of approximately a factor of 1.5 to 2 (factor of 2.25 to 4 in PSD) above the shot noise limit for 100 mA of photocurrent.[1]

Using a factor of 3 (PSD) above the shot noise for 100 mA implies that for the full 10 watts of output power (6.8 amps of photocurrent), $V = 137$. Here V is the PSD of the relative power fluctuations divided by the PSD of the relative power fluctuations for a shot noise limited beam.

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[1] This implies that the LIGO 10-W Laser does not meet the target specification of less than 2 dB above the shot noise at 10 MHz for 10 mA photocurrent. As shown above,