LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
–LIGO–
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note	**LIGO–T990025–00–D**	**03/08/99**

(Infrared) Pre-stabilized Laser (PSL) Final Design

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Distribution of this draft:
Detector

This is an internal working note
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1 Introduction

1.1 Purpose and Scope

The purpose of this document is to present the final design for the LIGO Pre-stabilized Laser (PSL). Data gathered from experiments conducted at Caltech and from the LIGO Hanford Observatory 2k Interferometer PSL is presented showing that the final design will meet the PSL design requirements.

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

1.2 Document Organization

1.2.1 Acronyms

AOM	acousto-optic modulator
ASC	Alignment Sensing and Control
CDS	Control and Data System
COC	Core Optics Components
COS	Core Optics Support
EOM	electro-optic modulator
HEPA	high efficiency particulate air
IOO	Input Optics
LHO	LIGO Hanford Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory
LSC	Length Sensing / Control
MIT	Massachusetts Institute of Technology
MOPA	master-oscillator-power-amplifier
Nd^{3+}:YAG	neodymium doped yttrium aluminium garnet
NPRO	non-planar ring oscillator
PMC	pre-modecleaner
PSL	pre-stabilized laser
PZT	piezo-electric transducer
rf	radio frequency
SEI	Seismic Isolation
SUS	
UNC	Unified National Coarse
VCO	voltage-controlled oscillator

1.2.2 Relevant Documents

1.2.2.1 LIGO Documents

- *EPICS Application Development Environment for LIGO Controls*, **LIGO–T960135-00-C**
- *Specifications LIGO 10-W Laser*, **LIGO–E970055–00–D**
- *(Infrared) Pre-stabilized Laser (PSL) Design Requirements*, **LIGO–T970080–09–D**
- *(Infrared) Pre-stabilized Laser (PSL) Conceptual Design*, **LIGO–T970087–04–D**
- *IR PSL CDS Conceptual Design Document*, **LIGO–T970114–00–C**
- *(Infrared) Pre-stabilized Laser (PSL) Electronics Design Requirements*, **LIGO–T970115–00–C**

- *Performance of VCO/AOM frequency shifter*, **LIGO–T970145–00–D**
- *Design study and test results for the PSL tidal actuator*, **LIGO–T980038–00–D**

1.2.2.2 Non-LIGO Documents

- *Diode-pumped CW Nd:YAG Master Oscillator Power Amplifier with Chiller and Controller Users Manual*
- *Supplement To 126–MOPA Users Manual: Electrical Subassemblies*
- *Specification for LIGO 10 W Laser Amplifier Electronics*

2 System Overview

The pre-stabilized laser (PSL) contains the laser source for the LIGO interferometer and is therefore located at the beginning of the optical train. The relationship between the PSL and other detector subsystems is shown in Figure 1. The laser is termed "pre-stabilized" because it has already received a degree of stabilization prior to being injected into the interferometer.

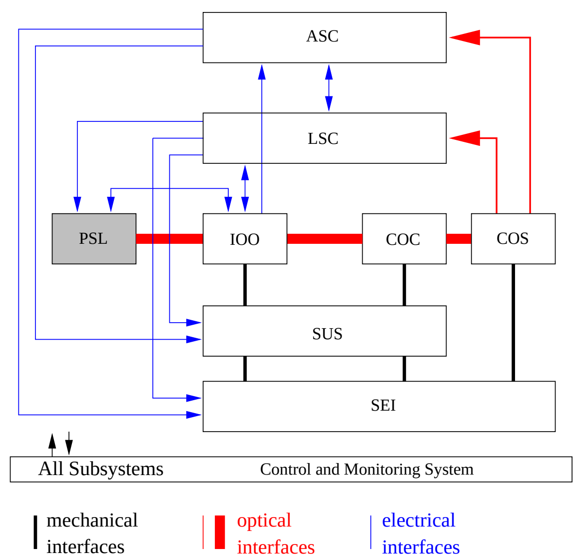

Figure 1: A block diagram showing the relationship of the PSL to other detector subsystems.

The PSL includes the LIGO 10-W Laser, called the 126 MOPA Laser by Lightwave Electronics, with power supply and recirculating water chiller; frequency stabilization electronics, intensity

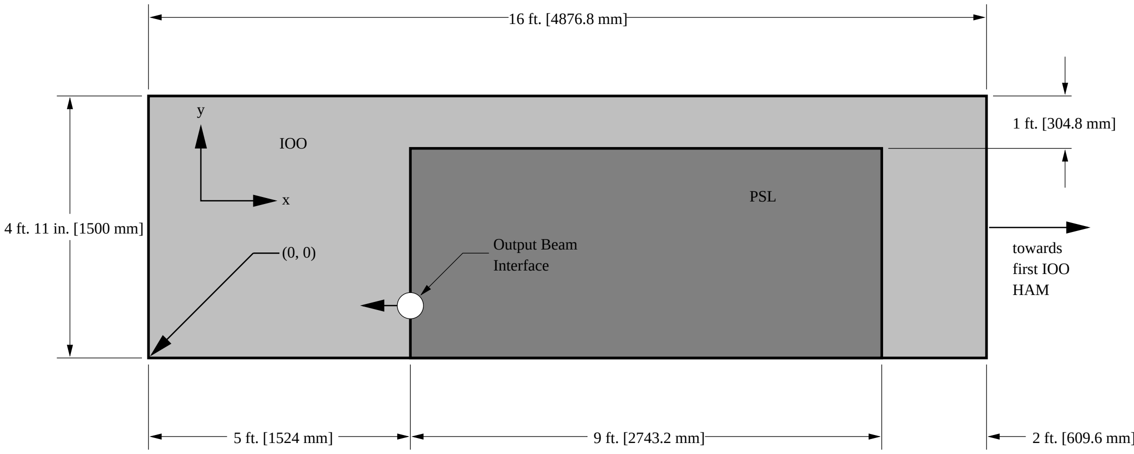

Figure 2: Relative positions of the PSL and IOO areas on the shared IOO / PSL optical table.

stabilization electronics, various optics and optical component mounting hardware, the optical table and optical table enclosure. It does not include any optics for the IOO or electro-optics for modulation frequencies used outside the PSL subsystem.

2.1 The IOO / PSL Optical Table

Figure 2 shows the division of the IOO / PSL optical table and the coordinate system employed in describing the interface between PSL and IOO. The whole optical table is enclosed inside a free-standing enclosure.

2.2 Optical Layout

The optical layout of the PSL is schematically illustrated in Figure 3. The output of the LIGO 10-W Laser is passed through a triangular ring pre-modecleaner (PMC) for spatial filtering and is intensity stabilized by an acousto-optic modulator (AOM) before being delivered to IOO. A small fraction of the output of the LIGO 10-W Laser has rf sidebands impressed on the light prior to being double-passed through a frequency shifting AOM. The double-passed output of the AOM is reflected by polarization selective optics towards the reference cavity. The output of the laser is frequency stabilized using the reflection locking scheme employed in LIGO.

2.3 Features and Capabilities

The PSL has internal actuators that can accommodate correction signals from IOO and LSC. The PSL provides a wideband frequency control input for frequency correction signals from the IOO modecleaner servo. In addition the PSL provides a tidal input for making the laser frequency track the common mode length changes of the interferometer arms on tidal time scales.

The PSL can be operated remotely via CDS. The performance of the PSL is monitored continuously and is logged for comparison with previous performance levels. Once installed, the operation of the PSL can be completely “hands off” with software routines taking care of lock acquisition and servo gain adjustment.

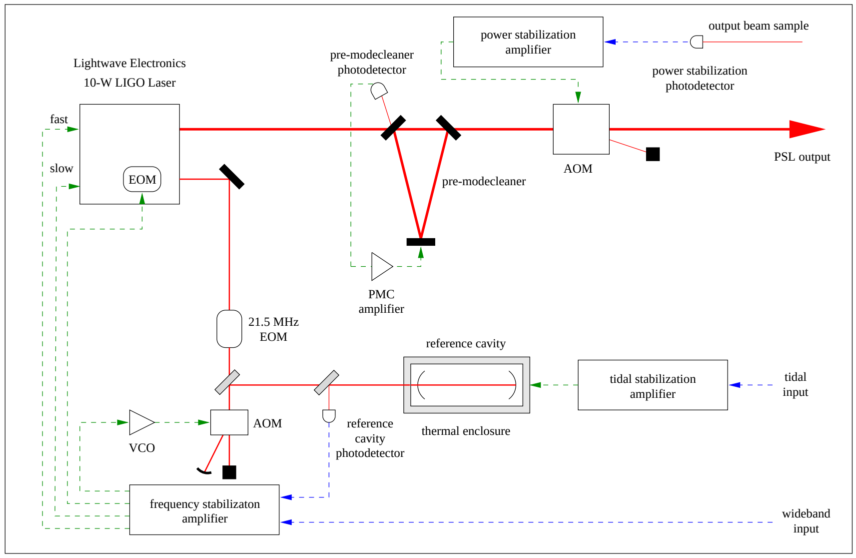

Figure 3: The optical layout of the PSL.

2.4 Experimental Results Achieved To Date

The results achieved with the LIGO Hanford Observatory (LHO) 2-km PSL either meet the design requirement or are very close to specification. It is felt that enough knowledge and experience has been gained with the LHO 2k PSL to deliver a laser that will meet all the design requirements in detailed *(Infrared) Pre-stabilized Laser (PSL) Design Requirements* **LIGO T970080–00–D**.

The results achieved include:

- Measured frequency noise levels being consistent with the design specification or better.
- Measured intensity noise levels at the IOO / PSL interface better than specification for frequencies higher than 700 Hz.
- A stabilized power output of 8 W, which is close to the requirement of 8.5 W.
- Automated lock acquisition of the frequency stabilization servo.
- Automated lock acquisition of the PMC servo.
- Simultaneous operation of frequency stabilization, PMC, intensity stabilization and tidal servos (demonstrated at Caltech).
- Continuous unattended operation for a period greater than 30 days. Without loss of lock, in the case of the frequency stabilization servo, and with only the occassional loss of lock in the case of the PMC servo — this is expected to be remedied with a pending design upgrade.

3 The 126 MOPA Laser

The 126 MOPA Laser was designed and developed under contract with LIGO by Lightwave Electronics Inc., Mountain View, CA. As its name suggests the laser is a master-oscillator-power-amplifier (MOPA) configuration consisting of a Model 126–1064–700 NPRO-based, diode-pumped, narrow-linewidth, single-frequency laser as the master oscillator and a double-passed power amplifier. The optical layout of the 126 MOPA Laser is shown in Figure 4.

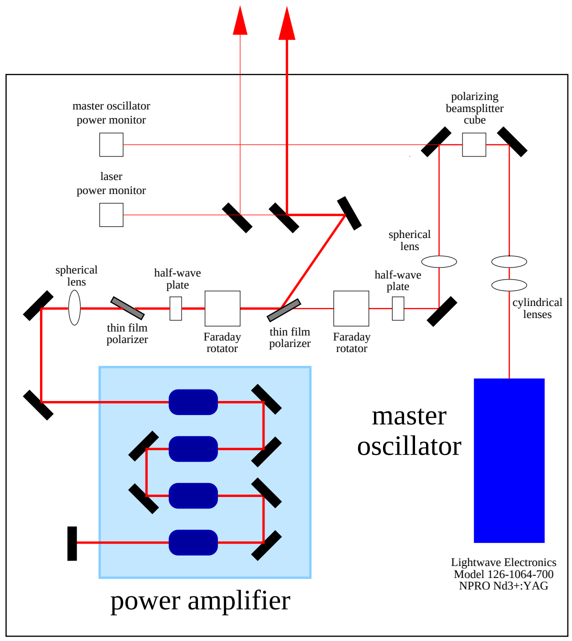

Figure 4: Optical layout of the Lightwave Electronics Inc. 126 MOPA Laser

The 126 MOPA Laser is mounted to a 2 ft. × 2 ft. optical breadboard with 1/4–20 UNC-2B tapped holes on a 1 in. grid. The breadboard is equipped with five Microlock Tiedowns[1]. Only three of the five Microlock Tiedowns are used to mount the laser to the surface of the optical table in order to maintain a three point contact.

All connections to the laser are made on the back of the laser head box, these include connections to the recirculating water chiller, laser power supply and the actuators of the laser. Two beams emerge from the laser: the main 10 W output beam and a nominal 50 mW beam sample. All optical components of the laser are enclosed within an aluminum case. The height of the 126 MOPA Laser, including the supporting optical breadboard, is approximately 8.5 in.

The final design review for the 126 MOPA Laser was held on June 20th, 1997 at Lightwave Electronics Inc. The engineering-prototype alpha unit, the Alpha-1 laser, arrived on October 21st, 1997. The first deliverable unit, the D-1 laser, arrived on January 16th, 1998. The second deliverable unit, the D-2 laser, arrived on April 1st, 1998.

4 126 MOPA Laser Features

4.1 Laser Output

The output wavelength of the 126 MOPA Laser is 1064 nm.

Two output beams emerge from the 126 MOPA Laser: the main 10 W beam and the 50 mW beam sample. This feature was not expected at the time of the PSL conceptual design but use of this feature has been made in the design presented in this document.

[1]Microlock Tiedowns is a registered trademark of Newport Corp.

The output of the 126 MOPA Laser is specified to be 10 W in a circular TEM_{00} mode, with a total power in all non-TEM_{00} modes to be less than 1 W. The output beam is s-polarized (vertical). The output beam spot size target specification is (0.22 ± 0.1) mm at a location (55 ± 50) mm from the output aperture of the laser, on the laser side.

4.2 Actuators

Three actuators are provided on the 126 MOPA Laser to control the output of the laser: two on the NPRO master oscillator and one on the power amplifier. The strategy presented in the conceptual design made use of the NPRO actuators for frequency tuning and the power amplifier AC current adjust actuator for stabilization of the output power. Specifications for the NPRO actuators can be found in the 126–1064–700 users manual.

4.2.1 Fast Actuator

The fast actuator is a PZT bonded to the Nd^{3+}:YAG crystal of the NPRO master oscillator. Fast frequency tuning of the 126 MOPA Laser is achieved via the fast actuator. The tuning coefficient for the fast actuator is approximately 5 MHz / V.

4.2.2 Slow Actuator

The slow actuator tunes the frequency of the NPRO master oscillator by heating or cooling the Nd^{3+}:YAG crystal. The tuning coefficient for the slow actuator is approximately 4 GHz / V.

4.2.3 AC Current Adjust Actuator

The AC current adjust actuator controls the current to the power amplifier pump diodes. The specifications for the AC current adjust actuator are given in Table 1.

Description	Specification
AC current adjust	± 10 V in $\Longrightarrow$ 0.1 A current change
input impedance	10 kΩ
frequency response	first pole $>$ 25 kHz, additional poles $>$ 100 kHz

Table 1: The power amplifier AC current adjust actuator specifications.

4.3 Laser Output Power Monitors

The 126 MOPA Laser comes equipped with two power monitors: one each for the NPRO master oscillator and one for the power amplifier. The output of the internal power monitors is available through the 64-pin system interface connector.

4.4 Integrated Power Supply

The 126 MOPA Laser comes with an integrated power supply from which the laser can be operated. In order to turn the laser on, the front panel key must be switched to the ON position. Two eight character orange LED displays indicate the status of the laser. Three rocker switches labeled "`Master Osc Standby`", "`Amplifier Standby`" and "`Shutter Close`" control the master oscillator, power amplifier and laser shutter respectively. In all cases the rocker switch overrides any external command input from a computer.

All connections to the power supply are made from the back panel. External control and monitoring of the laser is via the 64-pin system interface connector.

The power supply comes in a 3 unit high, 19 in. wide rack mount chassis and will be housed in the PSL electronics rack, along with other PSL-related electronics.

4.5 Water Cooling

Cooling of the 126 MOPA Laser is provided by a Neslab Instruments RTE-140 low-temperature bath / circulator. Operation of the bath is controlled via an RS–232 connection to the integrated power supply.

4.6 Mounting of the 126 MOPA Laser

The 126 MOPA Laser will be fastened to the IOO / PSL optical table via the Microlock Tiedowns in the laser breadboard. However only 3 of the 5 available Microlock Tiedowns will be used in order to provide for a more stress-free mount. To avoid making the breadboard conform to the IOO / PSL optical table surface, under each of the 3 Microlock Tiedowns there will be a set of steel spherical washers.

A set of spherical washers comes in two parts, with each part mating with each other on a spherical surface. The other surface of the parts is flat. Thus the flat sides of the spherical washers would face the IOO / PSL optical table and the laser breadboard. Whilst the breadboard is being fastened to the table surface, the spherical surfaces slide against each other. The use of these washers reduces the danger of warping the laser breadboard and therefore the risk of mis-aligning the laser.

4.7 126 MOPA Laser Performance

4.7.1 Output Power

All lasers delivered to Caltech produced more than 10 W when tested by Lightwave Electronics Inc. prior to shipping. When measured down at Caltech the output power of each laser was lower than that stated on the test report that accompanied the laser. A direct comparison of the calorimeters used did not explain the discrepancy in the power measured.

4.7.2 Output Mode

When tuned to a mode-hop-free region with the slow actuator, the TEM_{00} output of the 126 MOPA Laser was slightly astigmatic. Measurements of the M^2 value of the laser, conducted with a Photon Inc. BeamScan Model 0180 Laser Profiler, confirm that the laser is in general accordance with the target specifications, although not as good as stated in the laser test report.

Experienced gained in the PSL Laboratory, when swapping out one laser for another, indicates that the variation in spot size from one laser to another does not present a significant problem for the general optical layout of the PSL.

4.7.3 Free-running Frequency Noise

Measurements of the free-running frequency noise of both the Alpha-1 and D-1 lasers confirm that they perform within specification. Figure 5 shows an example of the measured free-running frequency noise of a LIGO 10-W Laser.

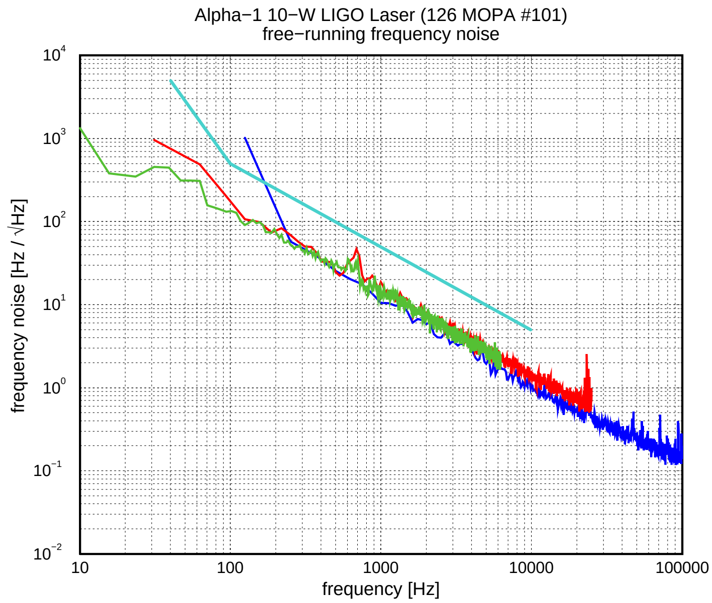

Figure 5: The measured free-running frequency noise of the LIGO 10-W Laser. The solid line drawn is the Lightwave Electronics target specification.

4.7.4 Free-running Intensity Noise

Measurements of the free-running intensity noise of the Alpha-1, D-1 and D-2 lasers confirm that the lasers perform within specification. An example of the free-running relative intensity noise of the 10-W LIGO Laser is shown in Figure 6.

4.7.5 Beam Pointing

Of the three lasers that have been tested, only the D-1 laser suffered from beam pointing problems. The problem was believed to be caused by a mechanical instability of the steel flexure mirror mounts used to align the beam from the master oscillator to the power amplifier. This problem was not encountered with the Alpha-1 laser, which was equipped with the same mirror mounts. Lightwave Electronics have replaced the steel flexure mirror mounts with a different style of mount that is believed to be more stable. The D-2 laser was the first laser to be equipped with this new style of mirror mount and no problems with beam pointing have been observed. The D-1 laser was returned to Lightwave Electronics for a mirror mount retrofit. All lasers are now equipped with the new style of mirror mount.

4.7.6 AC Current Adjust Actuator Transfer Function

The measured transfer function for the AC current adjust actuator is shown in Figure 7. Transfer function measurements performed on each laser showed that the frequency of the first pole in the actuator transfer function was less than the target specification of 25 kHz. The presence of the extra poles presents an enormous difficulty in designing a stable feedback control servo to regulate the intensity noise with this actuator.

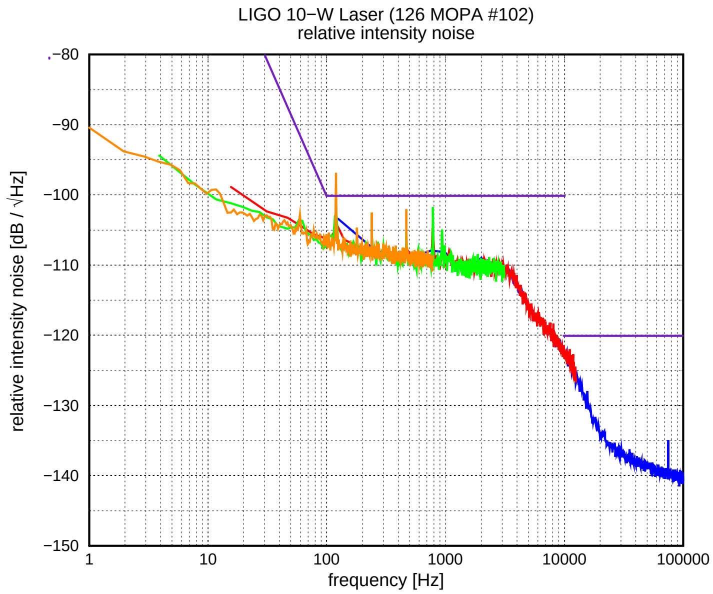

Figure 6: The measured free-running relative intensity noise of the LIGO 10-W Laser. The solid line drawn is the Lightwave Electronics target specification.

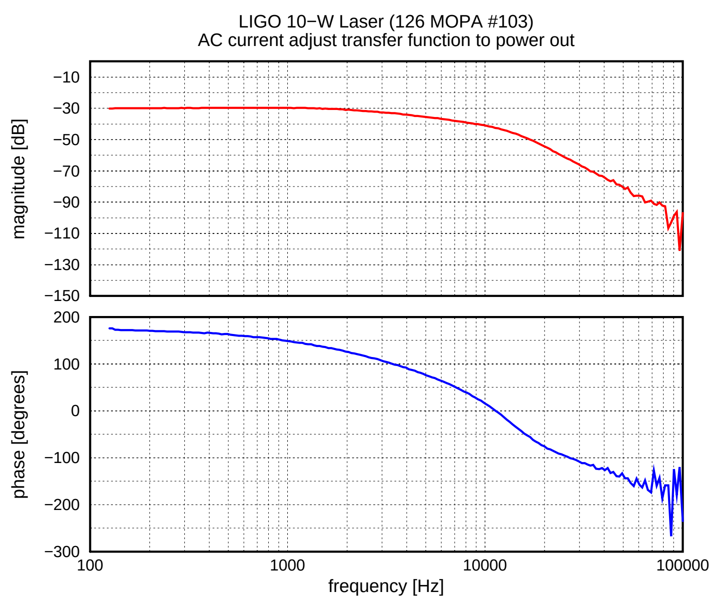

Figure 7: The transfer function of the AC current adjust actuator.

A number of approaches, using this actuator were tried, including a split loop approach between the power actuator of the master oscillator and the AC current adjust actuator and a current shunt actuator. Whilst the alternate approaches exhibited some promise, the development work necessary would have required more time than the schedule permitted. Therefore, a conventional approach

Laser Number	Status
#101	Alpha-1 engineering prototype, returned to Lightwave Electronics
#102	installed in the LHO 2k IFO
#103	repaired by Lightwave Electronics
#104	planned for LLO installation
#107	in PSL Lab

Table 2: Status of the 10-W lasers already delivered.

utilizing an AOM is employed.

5 126 MOPA Laser Performance To Date

To date five lasers have been delivered, including the Alpha-1 engineering prototype. Upon arrival, each were checked for conformance to the Lightwave Electronics target specifications. In all cases, the output power of the lasers was measured to be lower than that claimed by Lightwave Electronics. A direct comparison of calorimeters used, revealed that there was an approximate 0.5 W difference in reading between our calorimeter and the Lightwave Electronics calorimeter. However, this 0.5 W difference did not account for the discrepancy in reported values. The work around solution to this problem is to increase the diode current to the power amplifier pump diodes. This may come at the cost of a slight reduction in the lifetime of the pump diodes.

The other discrepancy lies in the reported values for the size and location of the output beam waist. This is perhaps the result of two different instruments being used, a Coherent ModeMaster at Lightwave Electronics and a Photon BeamScan at Caltech. This does not present a problem, however more work in improving the quality of the output beam is needed in order to make improvements to the modematching to the PMC.

Table 2 summarizes the status of the lasers received. Of the five lasers delivered, 126 MOPA #103 is the only laser that showed signs of power amplifier pump diode decay. The output power and beam quality of this laser degraded to the point where it was returned to Lightwave Electronics, who discovered that three out of the eight diode bars had deteriorated. The reasons behind the diode bar decay are not clear but are currently under investigation.

6 Physical Implementation

6.1 Optical Table Enclosure

The IOO / PSL optical table is enclosed in a 200 in. $\times$ 68 in. $\times$ 82.75 in. high free-standing enclosure, fabricated in two halves. The frame of the enclosure is fabricated from 2 in $\times$ 2 in. $\times$ 1/8 in. wall square cross-section steel tubing and is powder coated with a polyester TGIC white gloss. This particular coating was found to be the most resistant to burning on exposure to the 10-W laser beam. Each half of the enclosure has provision for four hoist rings to enable the enclosure to be lifted by crane.

All panels of the table enclosure are made from medium density fiber (MDF) board, laminated on all sides. The doors of the enclosure are laminated royal oak blue on the outside and white on the inside. Each half of the table enclosure has four doors per side and two doors at each end. Each door is fitted with a magnetic switch, which can be used for indicating that an enclosure door is open.

Inside the enclosure, lighting is provided by a series of track-mounted incandescent lamps. The position and angle of each lamp is able to be adjusted according to need. Each half of the enclosure has six lamps. Each lamp has its own on / off switch.

On top of the table enclosure are a pair of HEPA filter units that are rated 99.99 % efficient for 0.3 μm and larger particles. The HEPA filters are equipped with variable speed controls and will be activated whenever maintenance requiring opening of the 126 MOPA Laser is to be performed.

6.2 Optical Table

The IOO / PSL optical table is a Newport Corp. RS4000–516–24 table with tuned damping, supported by a set of NN6–10 non-isolating legs[2]. The dimensions of the table are a nominal 5 ft.×16 ft.×24 in. The actual width of the table is 59–1/16 in. The legs are 10 in. high with an adjustment range of over 2.5 in. The steel surface of the table is covered with 1/4–20 UNC-2B tapped holes on a 1 in. grid pattern, starting 1.5 in. from the short edge of the table and 1.53 in. from the long side of the table. The table surface is (35, +0.25, -0.00) in. from the LVEA floor.

Should performance of the non-isolating support legs be found to be inadequate, they can be replaced by a set of isolating support legs (e.g. I-2000 vibration isolators).

6.3 Beam Stops

In order to maintain a laser safe environment, beam stops are mounted to contain any stray beams or "leakage" beams through mirrors. Any beam powerful enough to be readily seen with an infrared viewer is stopped with a beam stop.

6.4 Optical Mounting Hardware

The following describes the hardware used to mount the various optical components at the PSL nominal optical height of 3 in.

6.4.1 Mirrors

Table 3 lists the components used to mount a 1.00 in. diameter mirror.

Item	Description	Part Number	Vendor
mirror mount	center mount	9807	New Focus
pedestal	2.00 in. high pedestal riser	9954	New Focus
clamp	short holding fork	9916	New Focus
screw	8-32 UNC-2A steel socket head cap screw, 0.50 in. long	N / A	N / A

Table 3: Component list for mounting 1.00 in. diameter mirrors.

6.4.2 Lenses

Table 4 lists the components used to mount a 1.00 in. diameter lens.

[2]The specifications and quotation solicitation for the tables are contained in **LIGO C972450–00–D**.

Item	Description	Part Number	Vendor
optic holder	lens mount for 1 in. optics	LMR1	Thorlabs
retaining ring	1.035-40 threaded retaining ring	SM1RR	Thorlabs
post	1 in. high stainless steel post	TR1	Thorlabs
screw	8-32 UNC-2A set screw, 0.50 in. long	N / A	N / A
post holder	1.50 in. high post holder	PH1.5–ST	Thorlabs
base	post holder pedestal base	9910	New Focus
clamp	short holding fork	9916	New Focus

Table 4: Component list for mounting 1.00 in. diameter lenses.

6.4.3 Cylindrical Lenses

Table 5 lists the components used to mount a 40 mm $\times$ 25 mm cylindrical lens. The mounts used for the cylindrical lenses allow the optic to be rotated for optimum adjustment of the focussing axis.

Item	Description	Part Number	Vendor
optic holder	Snap-In lens holder	35–4025	CVI Laser
lens mount	Quick-Change mount	Model 45	CVI Laser
post	modified stainless steel post	N / A	Thorlabs
post holder	1 in. high post holder	PH1-ST	Thorlabs
base	post holder pedestal base	9910	New Focus
clamp	short holding fork	9916	New Focus

Table 5: Component list for mounting cylindrical lenses.

6.4.4 Polarizing Beamsplitter Cubes

Table 6 lists the components used to mount a 0.50 in. polarizing beamsplitter cube. Both high-power and low-power polarizing beamsplitter cubes are employed in the PSL.

Item	Description	Part Number	Vendor
prism mount	prism / beamsplitter mount	9411	New Focus
shim	0.25 in. thick shim	9950	New Focus
pedestal	1.50 in. high pedestal	9953	New Focus
clamp	short holding fork	9916	New Focus

Table 6: Component list for mounting polarizing beamsplitter cubes.

6.4.5 Waveplates

Table 7 lists the components used to mount either a 1.00 in. diameter half-waveplate or quarter-waveplate. The waveplates used are 0.50 in. diameter mounted in a 1.00 in. diameter mounting ring. This configuration is available as a standard option from CVI Laser Corp. All waveplates used are zero-order waveplates.

Item	Description	Part Number	Vendor
rotary stage	manual rotary stage	9401	New Focus
pedestal	1.50 in. high pedestal	9953	New Focus
clamp	short holding fork	9916	New Focus

Table 7: Component list for mounting waveplates.

6.4.6 Electro-optic Modulators

Table 8 lists the components used to mount an electro-optic modulator (EOM).

Item	Description	Part Number	Vendor
pedestal	1.00 in. high pedestal riser	9952	New Focus
shim	0.25 in. thick shim	9950	New Focus
shim	0.125 in. thick shim	9950	New Focus
clamp	short holding fork	9916	New Focus
kinematic stage	four-axis tilt aligner	9071	New Focus

Table 8: Component list for mounting an EOM.

6.4.7 Pre-modecleaner Mode-matching Mirrors

In order to accurately mode match the laser light into the PMC, high stability mirror mounts with a fine adjustment capability are needed. It has been found that a suitable mirror mount for this purpose is the Newport Corp. SL series gimbal mirror / beamsplitter mount with differential micrometers. A spacer block is required to raise the optical height of the mirror mount to the PSL optical height. The components required for mounting the PMC mode-matching mirrors are listed in Table 9.

Item	Description	Part Number	Vendor
mirror mount	gimbal / beamsplitter mount	SL25.4BD	Newport
clamps	very compact table clamp	CL4	Thorlabs
spacer	gimbal mirror mount mounting block	D980671	PSL

Table 9: Component list for mounting the PMC mode-matching mirrors.

6.4.8 Frequency Shifting Acousto-optic Modulator

Table 10 lists the components used to mount the frequency shifting AOM. The frequency shifting AOM is mounted to a four-axis tilt stage via an adapter plate. The whole subassembly, in turn, is mounted to a micrometer driven translation stage.

Item	Description	Part Number	Vendor
translation stage	low profile crossed-roller bearing translation stage	426	Newport
actuator	manual drive micrometer	SM–25	Newport
spacer	adapter plate	D980672	PSL
kinematic stage	four-axis tilt aligner	9071	New Focus
spacer	adapter plate	D980673	PSL

Table 10: Component list for mounting the frequency shifting AOM.

6.4.9 Intensity Stabilization Acousto-optic Modulator

Table 11 list the components used to mount the AOM used for intensity stabilization of the PSL output.

Item	Description	Part Number	Vendor
kinematic stage	four-axis tilt aligner	9071	New Focus
spacer	adapter plate	N / A	PSL

Table 11: Component list for mounting the intensity stabilization AOM.

7 Frequency Stabilization

7.1 The Reference Cavity

The PSL reference cavity, shown in Figure 8, is a linear Fabry-Perot cavity consisting of an 203.2 mm long fused silica spacer with two mirrors that are optically contacted, one to each end of the spacer. The spacer is a right cylinder with an outer diameter of 50.8 mm and an inner diameter of 12.7 mm. Each end of the spacer is polished to a scratch-dig surface figure of 10–5 and flat to $\lambda/4$. In addition a 1.27 mm $\times$ 45 chamfer exists at each end. In the middle of the spacer is a 6.35 mm diameter vent hole which is bored from the outside of the spacer body through to the inner bore. The reference cavity is nominally identical to that used on the Phase Noise Interferometer (PNI) at MIT.

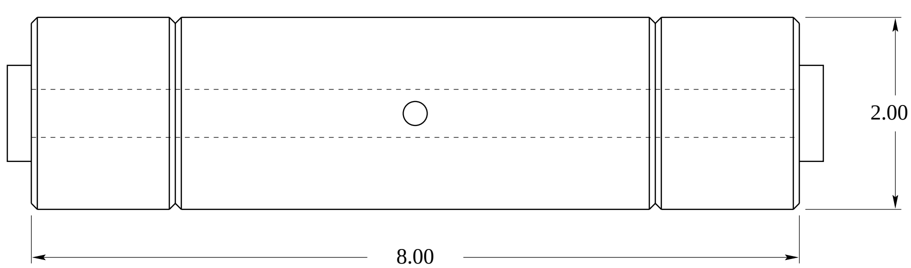

Figure 8: The reference cavity. Dimensions are in inches.

The reference cavity parameters are listed in Table 12.

mirror diameter	25.4 mm
mirror thickness	6.35 mm
mirror wedge angle	30 minutes
mirror transmittance	(300 ± 30) ppm
mirror absorptance	< 30 ppm
mirror back surface reflectance	< 500 ppm
cavity length	203.3 mm
cavity waist	237 μm
free-spectral range	736.5 MHz
finesse	9518
bandwidth (FWHM)	77.4 kHz
storage time	2.06 μs

Table 12: Reference cavity parameters.

7.1.1 The Reference Cavity Vacuum Chamber

The reference cavity vacuum chamber is based on a design used in the NPRO-PSL. The vacuum chamber is approximately 26 in. long, including the viewport flanges and is 8 in. in diameter. Each end of the vacuum chamber is fitted with 10 in. non-rotatable ConFlat[3] flanges. In addition three 2.75 in. ConFlat flanges are installed for the ion pump, shutoff valve and up-to-air valve. Around each chamber is a form-fit heater jacket which serves to keep the vacuum chamber at a steady temperature. Current control feedback to this heater forms the tidal servo required of the PSL to compensate for the length changes induced by tidal stretching of the Earth's crust.

Around the vacuum chamber an array of four temperature sensors is fitted. Analog Devices AD 590 temperature sensors are mounted to a printed circuit board, which is attached to nuts welded on the side of the reference cavity vacuum chamber. A 20 liter per second, single-ended ion pump keeps the vacuum chamber under vacuum at all times.

7.1.2 The Reference Cavity Vibration Isolation Stack

The reference cavity vibration isolation stack, based on that used in the NPRO-PSL, is a three layer isolation stack. Each layer is separated from each other by RTV springs. On the top plate sits four posts from which the reference cavity is suspended via a set of springs and lengths of steel music wire. Two eddy current motion dampers are attached at each end of the reference cavity to dampen any rocking motion of the reference cavity that might occur.

7.2 PSL Modulation Frequency

The modulation frequency used in the frequency stabilization electronics for the PSL is 21.5 MHz.

7.3 The Frequency Shifter

The AOM chosen for the frequency shifter is identical to that reported in *Performance of VCO / AOM frequency shifter* **LIGO T970145–00–D**. The components for the frequency shifter are given in Table 13. The input aperture of the AOM was slightly modified to permit placement of the beam closer to the transducer bonded to one side of the $PbMoO_4$ crystal. This modification allowed the single pass phase delay of the AOM to be reduced to 308 ns.

[3]ConFlat is a registered trademark of Varian Vacuum Products

Item	Description
AOM	Isomet 1205C–843
VCO	Synergy CRO-P-A03

Table 13: The frequency shifter components.

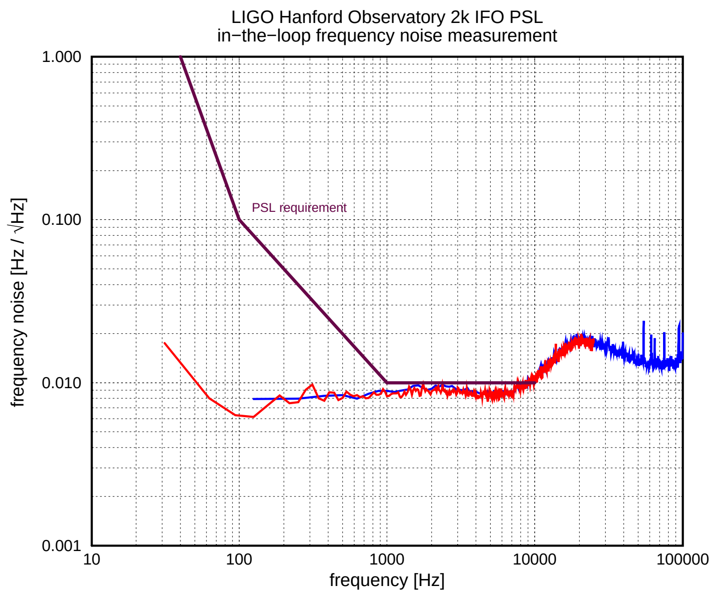

Figure 9: The in-the-loop frequency noise measurement conducted on the LHO 2k PSL. The solid line drawn is the PSL design requirement.

The typical insertion loss of the AOM is 2 %, with a single-pass diffraction efficiency of 90 % with a rf drive power of approximately 1 W.

The AOM is mounted onto a four-axis tilt aligner to optimize the alignment for maximum diffraction efficiency. The whole subassembly is mounted on top of a translation stage which travels in a direction perpendicular to the beam propagation direction. This permits the end of the AOM with the transducer to be positioned as close to the beam as possible, thereby minimizing the phase delay introduced by the AOM.

7.4 Frequency Stabilization Servo Performance

The frequency stabilization servo builds upon experience gained with the NPRO-PSL, with a few enhancements. The enhancements have resulted in a degree of robustness not experienced with the NPRO-PSL. In addition the electronics constructed are not specific to a particular LIGO 10-W Laser. In the PSL Lab at Caltech, three different 10-W lasers have been stabilized, all with the same electronics. Figure 9 shows the in-the-loop frequency noise measurement as measured on the LHO 2k PSL.

The reliability of the PSL is driven by the requirement:[4]

> "The PSL shall be designed to operate continuously without loss of 'lock' (even for

[4]See LIGO–T970080–09–D, Section 3.2.1.17.

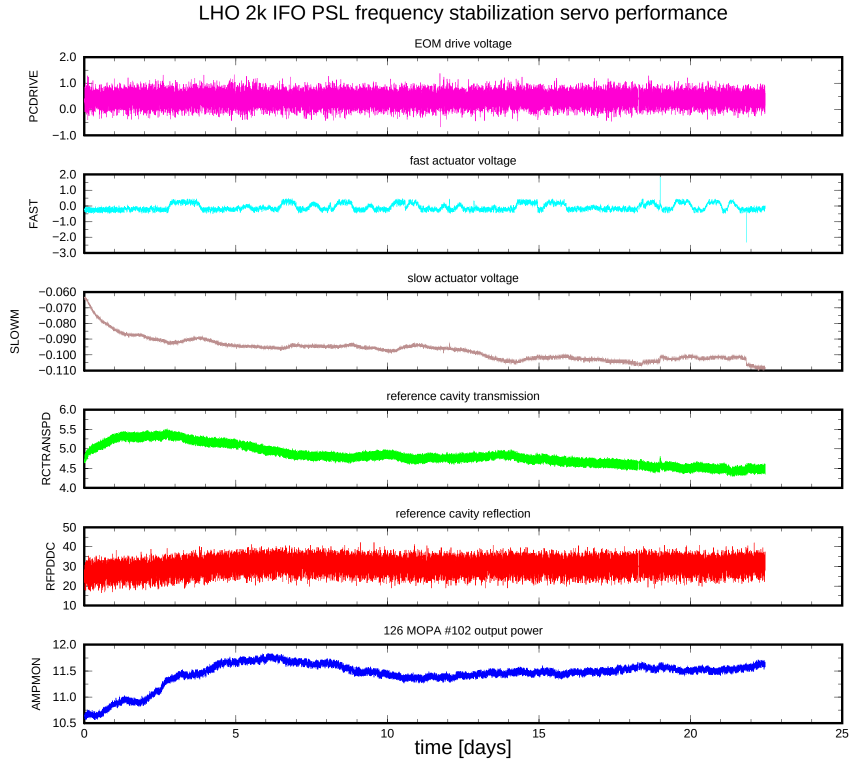

Figure 10: Time domain monitoring of the PSL frequency stabilization servo performance. The signals displayed are – from top to bottom – the signal to the phase-correcting EOM, the fast actuator voltage, the slow actuator voltage, the reference cavity transmission, the DC output of the 21.5 MHz photodetector and the unstabilized output power of the laser. The noise present in the signals plotted is due to a grounding problem encountered with the VME-bus analog-to-digital converters.

short times) for 40 hours, during normal seismic conditions (90 % percentile **TBD** by **SYS** for either site)."

Figure 10 shows signals associated with the frequency stabilization servo for a recorded duration of approximately 22 days. In fact the PSL remained locked to the reference cavity for a longer duration, only the computer logging the performance data was rebooted and data was not recorded when the computer was off-line.

7.5 PSL Wideband Frequency Control Input

The design specification for the PSL wideband frequency control input is:[5]

Frequency response:

Magnitude

DC to 100 kHz: Flat within 2 dB

$f > 100$ kHz: $< (f/100\,\text{kHz}) \times$ (average response below 100 kHz)

Phase: Phase lag at 100 kHz, $\phi < 20°$

[5] See LIGO–T970080–09–D, Section 3.2.3.1.2.1.

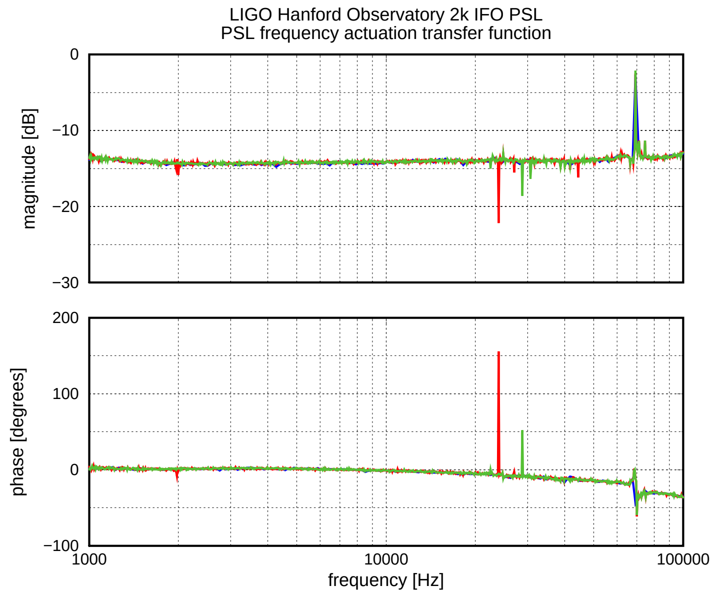

Figure 11: The frequency response of the PSL.

Figure 11 shows the measured PSL wideband actuator frequency response. This measurement was performed by sweeping the input to the VCO, which drives the frequency shifting AOM, with a dynamic signal analyzer and looking at the error signal from the PMC servo.

The spikes present in Figure 11 at approximately 25 kHz are believed to be environmental, since it is not present in both data traces plotted. The spike located at 70 kHz is due to the resonance of the PZT used in the PMC. The magnitude response is close to the required flatness. The phase lag at 100 kHz is greater than the requirement due to the response of the high voltage amplifier used to drive the phase-correcting EOM. However it is felt that it will be possible to meet the requirement with an optimized high voltage amplifier design. Another high voltage amplifier design was tried and exhibited a better phase response, however this came at the cost of robustness. As a result, it was not deployed in the LHO 2k PSL.

7.6 PSL Tidal Correction Frequency Control Input

For an in depth discussion of the laboratory test results obtained with the PSL tidal actuator, see *Design study and test results for the PSL tidal actuator* **LIGO T980038–00–D**. Figure 16 shows the measured response of the PSL to the tidal actuator setpoint input. The temperature stabilization achieved was ± 0.1 K. The temperature stability of the reference cavity vacuum chamber is shown in Figure 13. The experimental tidal actuator setup is shown in Figure 12.

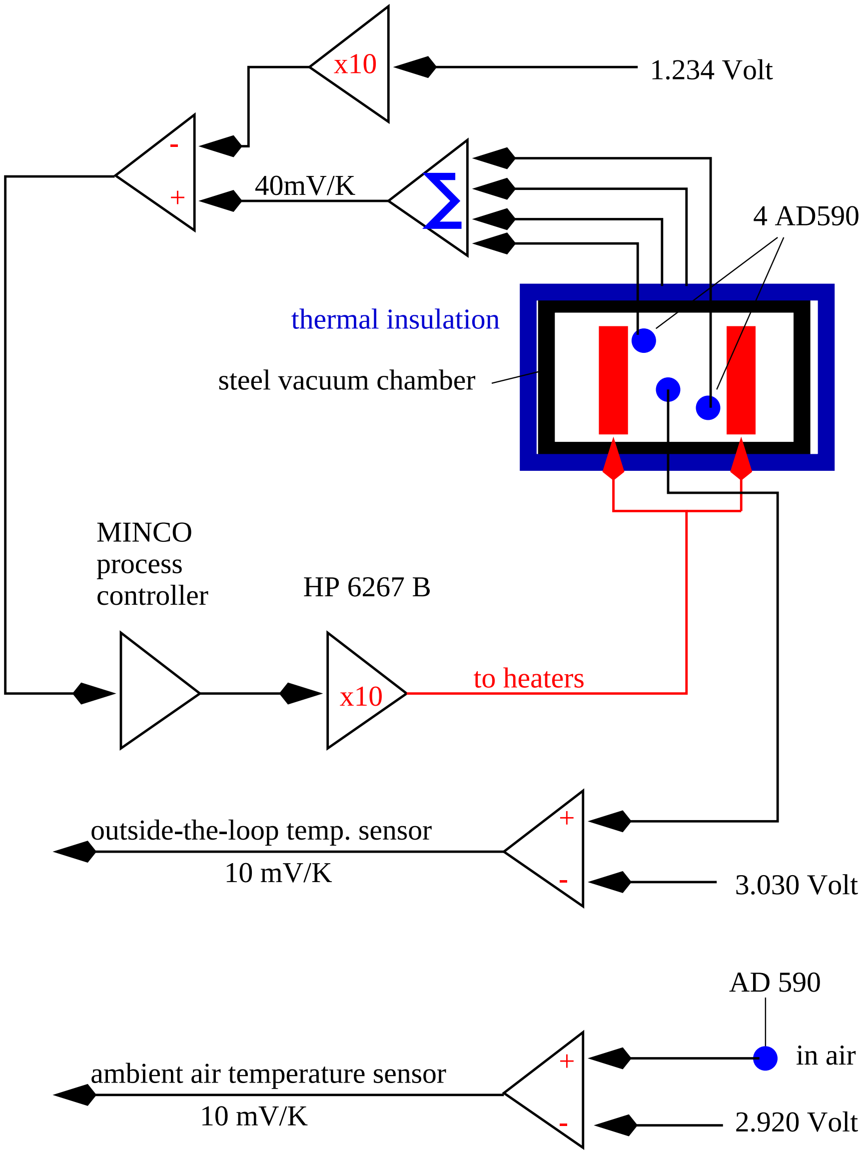

Figure 12: The setup used for the PSL tidal actuator.

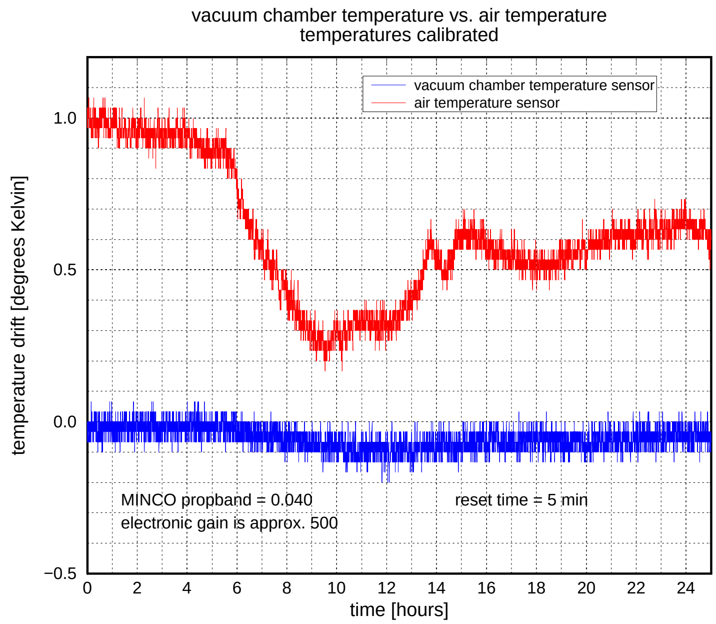

Figure 13: Air temperature versus the reference cavity vacuum chamber temperature, as monitored by an outside-the-loop temperature sensor.

Two time constants are important in the tidal servo:

- The time taken for the reference cavity vacuum chamber to respond to a step input from the heater, τ_{heat}.
- The time taken for the laser frequency to respond to a step input from the heater, τ_{rad}.

Experimentally τ_{heat} was determined to be 30 minutes and τ_{rad} 172 minutes (see Figures 14 and 15).

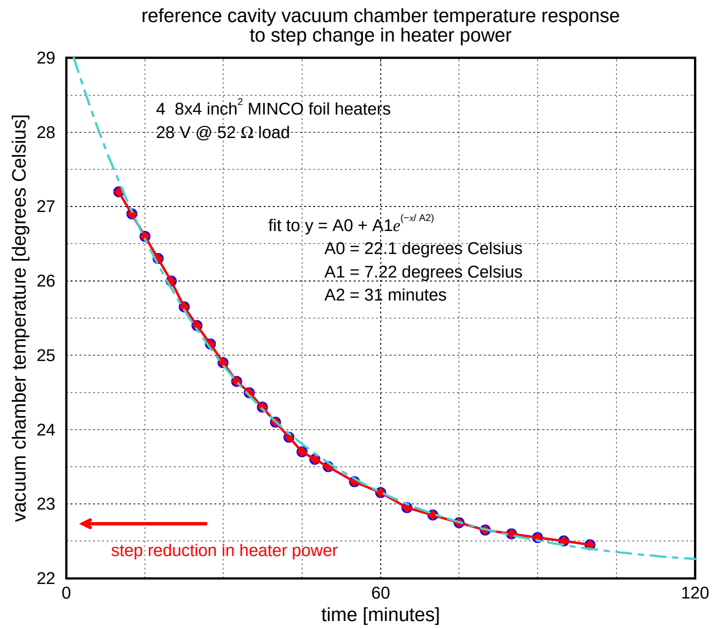

Figure 14: The step response of the reference cavity vacuum chamber temperature after decreasing the heater power. Temperatures were measured with K-type thermocouples.

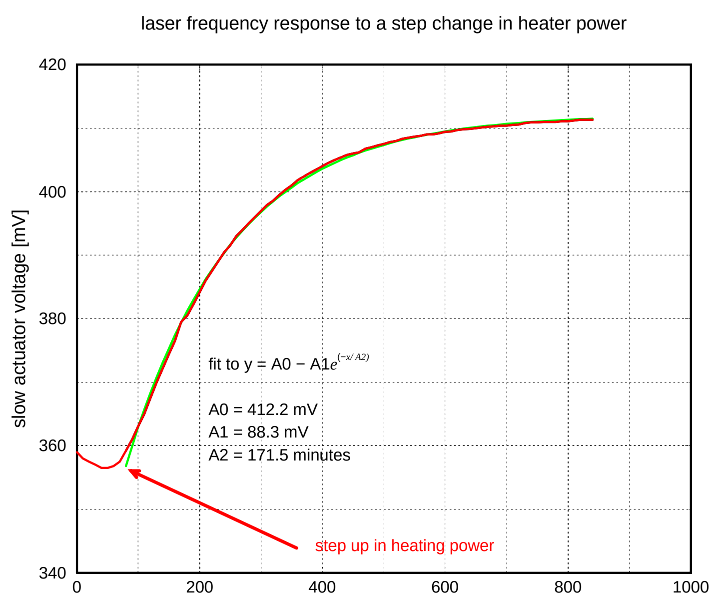

Figure 15: The step function response of the laser frequency to a step increase in heater power.

The experimental results were obtained with heaters that only partially (≈ 35 %) covered the surface of the reference cavity vacuum chamber. The custom fit heaters designed for the reference cavity vacuum chamber almost cover the entire surface area and can deliver a maximum of 120 W

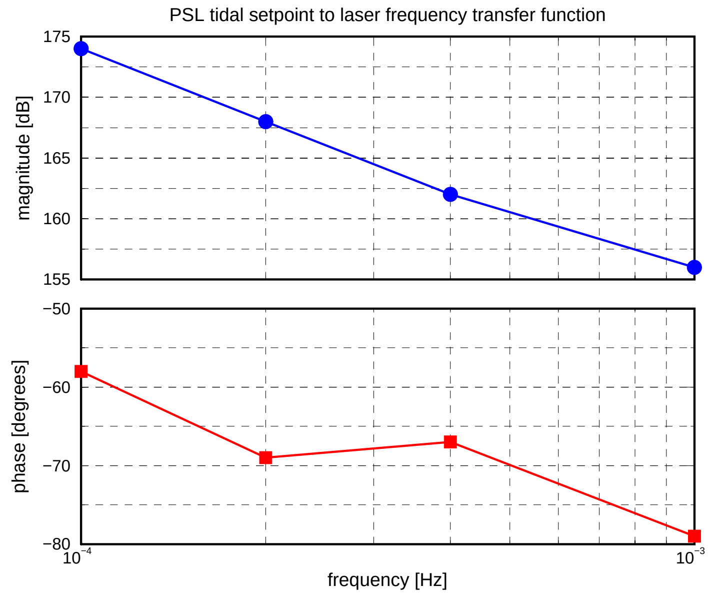

Figure 16: The tidal actuator response.

of heating power. Better performance is expected with the new heaters.

8 Power Stabilization

The PSL has three requirements on its power stability. First there are the low-frequency variations in the output power of the PSL. Second, the relative power fluctuations in the gravitational-wave band and third, there is a stringent requirement on the shot-noise-limited power fluctuations at the interferometer modulation frequency. Each requirement is satisfied by a different control strategy.

8.1 Low Frequency Power Fluctuations

The requirement for low-frequency variations in the PSL output power is:[6]

> "The low-frequency variations in the PSL output power shall be less than 1 % peak-to-peak over any 24-hour period."

The target Lightwave Electronics specification for low-frequency power fluctuations is:

> "Relative Power Fluctuations, $\delta P(f)\,/\,P$:
> Drift over 24 hours $< 1\,\%$ peak to peak."

Experience gained with the LIGO 10-W lasers to date, indicate that only some of the lasers meet this requirement. This is also confirmed by test reports that accompany each laser.

The 126 MOPA Laser has two internal power monitors, one each for the master oscillator and power amplifier. The signals from these power monitors, `PSL-126MOPA_126MON` and `PSL-126MOPA_AMPMON` respectively, are monitored by computer. The laser output power can be adjusted via two independent actuators, the power actuator on the master oscillator and the current to the power amplifier

[6] See LIGO–T970080–09–D, Section 3.2.1.4.

pump diodes. Computer monitoring of the laser output power will indicate if it is necessary to make any adjustments to the laser. This can be done using a software control loop, via the EPICS interface.

8.2 Fractional Light Power Fluctuations in the GW Band

The PSL is required to provide power stabilized light to both IOO and COC. The requirement at the input to IOO is:[7]

> "The amplitude spectral density of the fractional light power fluctuations at the input to the IOO shall be $\delta P(f)\,/\,P < 10^{-6} 1\,/\,\sqrt{\mathrm{Hz}}$ for $100\,\mathrm{Hz} < f < 10\,\mathrm{kHz}$ and rising as $f^{-3/2}$ for $40\,\mathrm{Hz} < f < 100\,\mathrm{Hz}$."

Owing to the frequency response of the AC current adjust actuator, the strategy for controlling the intensity fluctuations of the PSL changed. The new strategy utilizes an AOM which diffracts light from the main beam in order to stabilize the intensity. The AOM modulator components are listed in Table 14.

Item	Description
Isomet 1201E-2	acousto-optic modulator
231-2	analog driver
RFA-108	rf amplifier

Table 14: The components of the intensity stabilization acousto-optic modulator.

The measured relative intensity noise at the IOO/PSL hand-off point for the LHO 2k IFO PSL is shown in Figure 17. The out-of-the-loop measurement shows that the PSL is within specification beyond 700 Hz. The result was obtained with a control servo whose loop shape was not optimized for the components listed in Table 14. When the gain was increased for further noise suppression, the servo started oscillating. It is felt that when the loop shape is optimized, then the intensity stabilization servo will be able to suppress the intensity fluctuations to the required level.

8.3 Shot-noise-limited Power Fluctuations

The requirement for shot-noise-limited power fluctuations is:[8]

> "The amplitude spectral density of relative power fluctuations in the output beam of the PSL, measured at the input to the IOO, at frequencies above 24.5 MHz and 29.5 MHz (the modulation frequencies of the sidebands used for gravity wave detection for the 4-km and 2-km interferometers, respectively), shall be less than 1.005 times the shot noise limit for 600 mW of laser light. (This is the expected power level at the dark port of the interferometer)."

The PMC is a small triangular ring cavity whose function is two-fold: to remove non-TEM_{00} modes from the output of the PSL and to act as a passive filter to reduce the intensity fluctuations at the modulation frequencies. When originally proposed, no high frequency intensity noise data for the master oscillator was available. It was assumed that the master oscillator was shot noise limited at 24.5 MHz and as a result, the PMC bandwidth had to be 3.3 MHz. However high frequency measurements of the intensity noise of the master oscillator, conducted after the arrival of the Alpha-1 10-W Laser, revealed that the master oscillator is not shot noise limited at the

[7] See LIGO–T970080–09–D, Section 3.2.1.5.
[8] *ibid.* Section 3.2.1.7.

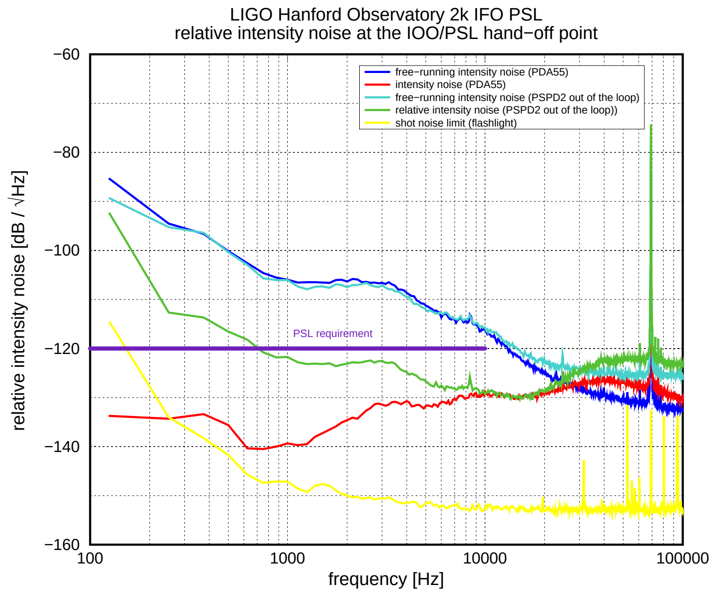

Figure 17: The relative intensity noise as measured at the input to IOO. Both in-the-loop and out-of-the-loop noise measurements are presented. The PSL requirement is the line drawn at -120 dB / $\sqrt{\text{Hz}}$.

modulation frequency. As a result, the bandwidth of the PMC was too large to achieve the required degree of filtering.

8.3.1 Pre-modecleaner Modulation Frequency

The modulation frequency used for locking the PMC is 35.5 MHz. The modulation sidebands are injected into the phase-correcting EOM located between the master oscillator and the power amplifier. The technique of summing the PMC sidebands with the phase-correction signal for the frequency stabilization servo does not appear to detriment the behavior of either the frequency stabilization servo or the PMC servo.

8.3.2 Pre-modecleaner Design

The existing PMC design is similar to that developed by N. Uehara at Stanford University. The parameters for the PMC are listed in Table 15. The PZT originally used had a resonance at 10 kHz which caused design complications for a servo to suppress the free-running length noise of the PMC. Length noise imparts frequency noise to the light resonating in the PMC cavity. In order to not add frequency noise and meet the PSL's frequency noise specification, the length noise needs to be suppressed. Two small design modifications were made to the size of the end mirror and the PZT used. The new PZT has a resonance of 74 kHz which permitted a wider servo bandwidth. The error spectrum for the PMC is shown in Figure 18.

cavity length	210 mm
cavity waist	371 μm
free-spectral range	713.8 MHz
finesse (low)	210
finesse (high)	4100
bandwidth (low)	3.3 MHz
bandwidth (high)	174 kHz

Table 15: The PMC cavity parameters.

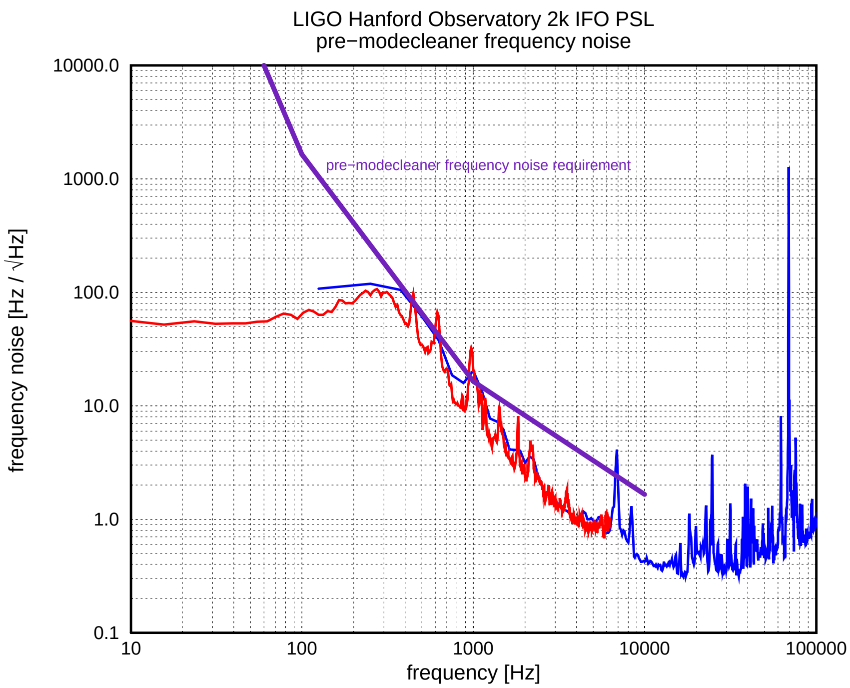

Figure 18: The frequency noise of the PMC.

The limiting factor on the performance of the PMC is a mechanical resonance of the fused silica spacer. The calculated resonant frequency of the spacer is approximately 9 kHz. Pending a redesign of the spacer block and perhaps the use of a material other than fused silica, it is expected that the resonance frequency of the spacer can be raised.

Another important design parameter of the PMC is the cavity bandwidth, which influences the degree of passive filtering provided by the PMC. Figure 19 shows the measured relative intensity noise at high frequencies, before and after the PMC, for two different photocurrents, 100 mA and 50 mA, corresponding to 150 mW and 75 mW of power respectively.

The intensity noise N_L before the PMC is approximately 6 dB higher than the intensity noise after the PMC. Writing the intensity noise after the PMC as N_{PMC} we have:

$$N_L = 2\, N_{PMC}. \tag{1}$$

The 100 mA measurement is approximately 3 dB higher than the 50 mA measurement, which

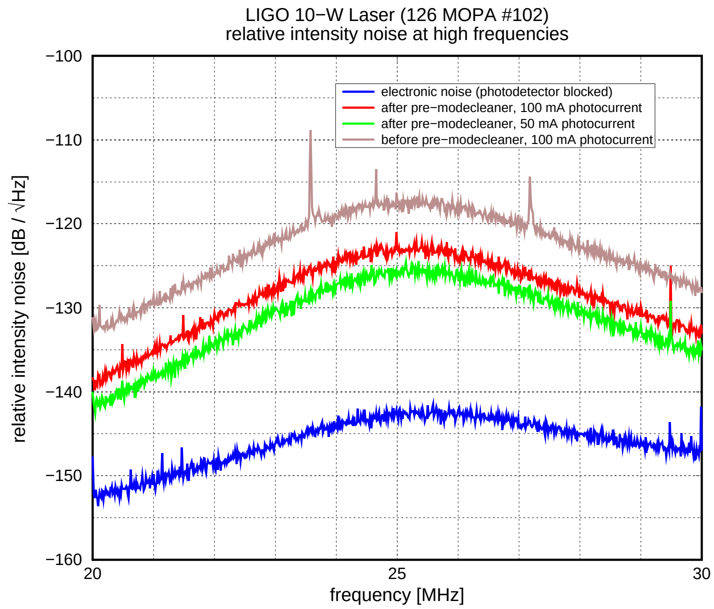

Figure 19: The measured relative intensity noise at high frequencies for 50 mA and 100 mA of photocurrent, before and after the PMC.

implies that the photodetector is shot noise limited at 25 MHz for more than 50 mA of detected photocurrent and the light after the PMC is shot noise limited at 25 MHz for more than 50 mA of photocurrent. Therefore N_{PMC}

$$N_{PMC} = N_{SN}. \tag{2}$$

The intensity noise has contributions from the shot noise N_{SN} and the technical noise N_T of the laser and is given by:

$$N_L = \sqrt{N_t^2 + N_{SN}^2} \tag{3}$$

Thus

$$N_T = N_{SN}\sqrt{\frac{N_L^2}{N_{SN}^2} - 1} \tag{4}$$

$$= N_{SN}\sqrt{3} \tag{5}$$

which is only true for 100 mA of photocurrent, or alternatively 150 mW of detected power. However the output of the laser is 10 W, which is 67 times the detected power of 150 mW. Therefore, the technical noise for 10 W of power, $N_{T\,10W}$, is given by:

$$N_{T\,10W} = 67\, N_T \tag{6}$$

and the shot noise for 10 W of power, $N_{SN\,10W}$, is given by

$$N_{SN\,10W} = \sqrt{67}\, N_{SN} \tag{7}$$

Combining these results gives

$$\frac{N_{T\,10W}}{N_{SN\,10W}} = \sqrt{67}\,\frac{N_T}{N_{SN}} \tag{8}$$

$$= \sqrt{67}\,\sqrt{3} \tag{9}$$

Therefore the experimentally derived technical noise amplitude spectral density of the 126 MOPA Laser is 14 times greater than the shot noise of 10 W.

The design requirement is that the relative intensity noise should be less than 1.005 times the shot noise limit for 600 mW of laser light, *i.e.*

$$N_{600\mathrm{mW}} < 1.005\; N_{SN\,600\mathrm{mW}}. \tag{10}$$

Equation 4 gives

$$N_{T\,600\mathrm{mW}} = N_{SN\,600\mathrm{mW}}\sqrt{1.005^2 - 1} \tag{11}$$

From the design requirement,

$$N_{T\,10W} = \frac{10}{0.6}\,N_{T\,600\mathrm{mW}} \tag{12}$$

and

$$N_{SN\,10W} = \sqrt{\frac{10}{0.6}}\,N_{SN\,600\mathrm{mW}}, \tag{13}$$

what the technical noise at 10 W should be in order to meet the design requirement is

$$N_{T\,10W} = \sqrt{\frac{10}{0.6}}\sqrt{1.005^2 - 1}N_{SN\,10W} \tag{14}$$

$$= 0.41N_{SN\,10W} \tag{15}$$

In order to meet this requirement, the technical amplitude spectral density of the 126 MOPA Laser has to be 0.41 times the shot noise limit for 10 W, $N_{SN\,10W}$. Comparing the measured result with the design requirement, the technical noise of the laser needs to be attenuated by a factor of $14\,/\,0.41 \approx 35$ at 25 MHz. The filtering H of a cavity is described by

$$H = \frac{1}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}} \tag{16}$$

where f is the frequency of interest and f_c is the cavity half-bandwidth. Thus a cavity half-bandwidth of 714 kHz is needed to obtain the desired level of filtering. The measurements presented were obtained by running the PMC in the "low finesse" mode where the cavity bandwidth is 3.3 MHz. Simply rotating the incident polarization from p to s swaps the PMC to run in the "high finesse" mode, where the cavity bandwidth is 174 kHz. This change should easily provide the degree of filtering required. However the circulating intensity inside the PMC is increased approximately 20-fold. Whether or not the mirror coatings can handle this increase in circulating intensity for an extended period of time is not presently known. Experiments to be conducted at Caltech will provide information on this subject.

Alternatively a PMC with a bandwidth of 714 kHz and a finesse of ~ 1000 can be constructed. This would increase the circulating intensity inside the PMC by a factor of approximately 5, making damage to the mirror coatings less likely.

8.3.3 Measured PSL Performance

Figure 20 shows the relative intensity noise as measured at the output of the PSL from 0–10 MHz. Figure 21 shows the relative intensity noise from 10–100 MHz. The peaks present in the spectra at around 1.5–2 MHz are believed to be caused by the intensity stabilization AOM, since measurements taken before the PMC do not exhibit these spikes.

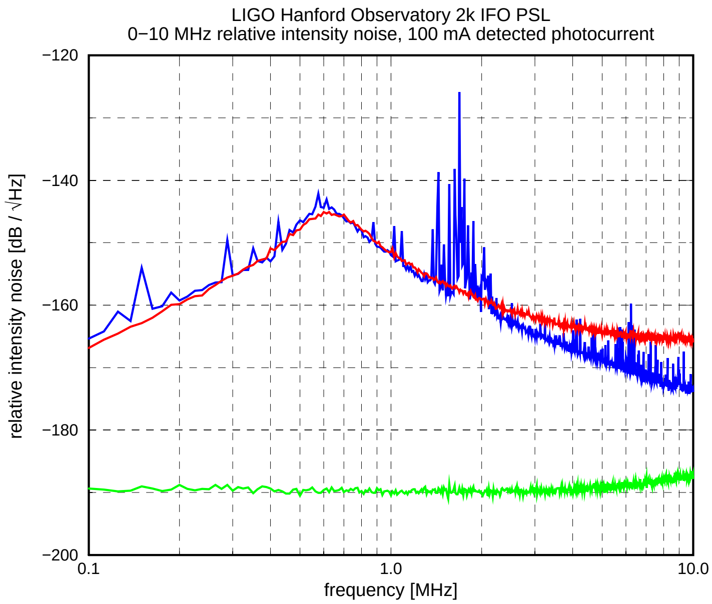

Figure 20: The low frequency relative intensity noise measured at the output of the PSL. The measurements were for 100 mA of detected photocurrent.

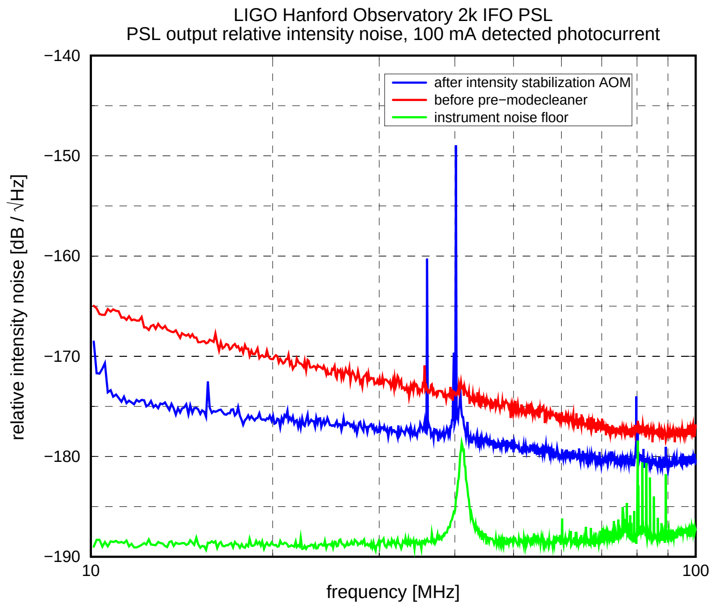

Figure 21: The low frequency relative intensity noise measured at the output of the PSL. The measurements were for 100 mA of detected photocurrent.

9 Output Power

The PSL is required to deliver 8.5 W of intensity stabilized light to IOO. The LHO 2k PSL delivers approximately 8 W of intensity stabilized light to IOO and does not meet the PSL requirement. It is still felt that the 8.5 W requirement is still achieveable once more experienced is gained with mode matching into the PMC and improvements are made to the output mode of the 126 MOPA Laser. It should be noted that the 8.5 W requirement can be met, if either the current to the power amplifier pump diodes is increased or the master oscillator output power is increased. Both approaches have the drawback of possibly reducing the lifetime of the laser.

10 Computer Control Interface

All operational modes of the PSL will be accessible via CDS.

11 Software Implementation

The control software for the PSL is written in State Notation Language (SNL) and runs under the Experimental Physics Industrial Control System (EPICS). Implementation of the control screens is under the Motif Editor and Display Manager (MEDM).

11.1 EPICS Records

All signal names in the PSL EPICS records database conform to the LIGO CDS standard. An example is the record for the output of the 126 MOPA Laser.

```
record(ai,"H2:PSL-126MOPA_AMPMON")
{
        field(DESC,"AMPMON- power amplifier monitor")
        field(SCAN,".5 second")
        field(DTYP,"VMIVME-3113")
        field(INP,"#C0 S0 @")
        field(PREC,"2")
        field(LINR,"LINEAR")
        field(EGUF,"12.50")
        field(EGUL,"-12.50")
        field(EGU,"watts")
        field(HOPR,"12.5")
        field(LOPR,"0")
}
```

11.2 PSL Servo Settings

All the settings of the various PSL servos are recorded with the Back Up and Restore Tool (BURT). This enables the data values to be restored in the event of an input / output controller (IOC) being rebooted.

12 User Interface

The user screens for the PSL are nested. The top level PSL control screen allows the user to ascertain "at a glance" what the status of the PSL is. If more specific knowledge of a particular servo is desired, the screen related to that particular servo can be accessed from the top level screen. Figure 22 shows the top level PSL control screen. More experienced users can access the particular servo screen directly from MEDM.

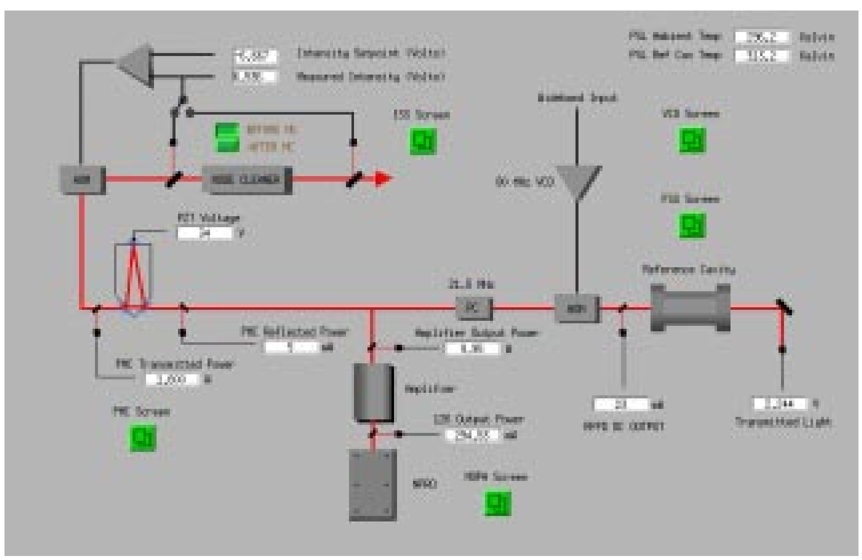

Figure 22: The top level PSL control screen.

Presented in this document is the first cut at the PSL user interface. The features and layout of the screens may change according to user feedback and experience gained.

12.1 The MOPA Screen

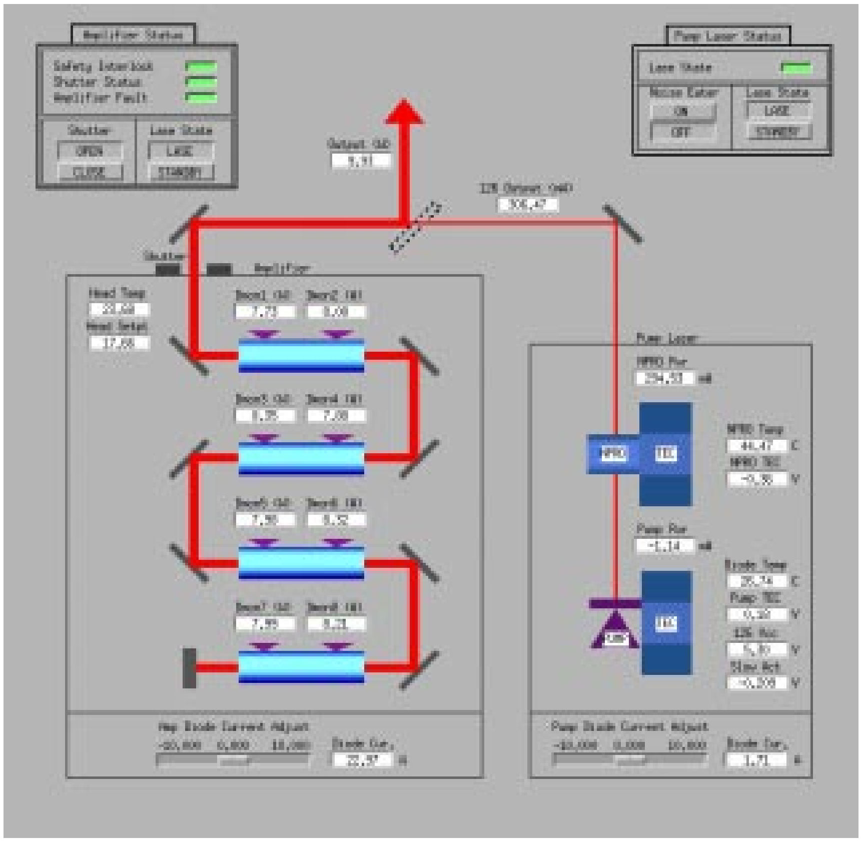

Figure 23: The MOPA screen.

The MOPA screen permits the user to access all the controls of the 126 MOPA Laser. Logically the screen is divided into left and right halves, with the right half of the screen being related to master oscillator controls. Controls relating to the power amplifier are located in the left half of the screen.

For the power amplifier, buttons control the status of the shutter and the status of the power amplifier. A slider control is provided to vary the current going to the power amplifier pump diodes. As the shutter is opened or closed, the drawn output of the laser animates according to the status of the shutter. That is, for example, if the shutter were closed there would be no 10 W output from the laser but the beam from the master oscillator would still be drawn up to the shutter.

The lase state and the noise eater for the master oscillator are controlled by two buttons located in the top right hand side of the screen. In addition the current to the master oscillator pump diode can be adjusted by a slider.

Displays are provided for other signals that are monitored. For example, the voltage from the monitor located over each power amplifier pump diode is displayed on the screen. Table 16 lists the signals monitored.

Signal Name	EPICS Name	Description
AMPMON	PSL-126MOPA_AMPMON	10 W laser output monitor
126MON	PSL-126MOPA_126MON	NPRO laser output monitor
DS1	PSL-126MOPA_DS1	diode sense 1
DS2	PSL-126MOPA_DS2	diode sense 2
DS3	PSL-126MOPA_DS3	diode sense 3
DS4	PSL-126MOPA_DS4	diode sense 4
DS5	PSL-126MOPA_DS5	diode sense 5
DS6	PSL-126MOPA_DS6	diode sense 6
DS7	PSL-126MOPA_DS7	diode sense 7
DS8	PSL-126MOPA_DS8	diode sense 8
126PWR	PSL-126MOPA_126PWR	NPRO laser output monitor
DTMP	PSL-126MOPA_DTMP	pump diode temperature
DMON	PSL-126MOPA_DMON	pump diode output monitor
LMON	PSL-126MOPA_LMON	NPRO output before fiber
CURMON	PSL-126MOPA_CURMON	diode current monitor
DTEC	PSL-126MOPA_DTEC	thermoelectric cooler temperature voltage
CURMON2	PSL-126MOPA_CURMON2	diode current monitor
HTEMP	PSL-126MOPA_HTEMP	power amplifier head temperature
HTEMPSET	PSL-126MOPA_HTEMPSET	power amplifier head temperature setpoint

Table 16: Signals displayed on the MOPA screen.

12.2 The FSS Screen

The FSS screen permits the user to control the behavior of the frequency stabilization servo. Various monitoring signals are displayed on the screen. There are four slider controls on the screen. The "`Input Offset Adjust`" zeroes out any voltage offsets present in the mixer on the frequency stabilization servo card. The "`Fast Gain Adjust`" adjusts the gain in the phase-correcting EOM loop, or the so-called "fast path". Once this gain is correctly adjusted, that is when the relative gains between the phase-correcting EOM and the fast actuator is correct, the "`Common Gain Adjust`" is then adjusted to lower the frequency noise down to the required level. The "`Slow DC Adjust`" adjusts the voltage applied to the slow actuator of the master oscillator. Figure 24 shows the FSS screen.

At the top of the screen are located two buttons that activate switches, allowing signals to be injected into connections in the frequency stabilization servo front panel. These switches should be enabled when transfer function measurements of the frequency stabilization servo are made. In the left hand corner of the FSS screen, is the automatic lock acquisition button. When "`ACQUIRE`" is depressed, the frequency stabilization servo will seek to automatically acquire lock to the reference cavity. This is a hands off process, requiring no intervention on the part of the user, other than activating the button.

At the bottom of the screen, monitors display the transmission and reflection of the reference cavity. Table 17 tabulates the monitoring signals displayed on the FSS screen.

EPICS Name	Description
PSL-FSS_RFPDDC	21.5 MHz photodetector DC output
PSL-FSS_LODET	detected 21.5 MHz local oscillator output
PSL-FSS_PCDET	detected EOM drive
PSL-FSS_FAST	fast actuator input
PSL-FSS_PCDRIVE	
PSL-FSS_RCTRANSPD	reference cavity transmission
PSL-FSS_VCODET	detected rf output to the frequency shifting AOM
PSL-FSS_TIDALOUT	drive to the reference cavity heater
PSL-FSS_MODET	21.5 MHz oscillator output power
PSL-FSS_MINCOIN	Minco process controller input
PSL-FSS_MINCOOUT	Minco process controller output
PSL-FSS_RMTEMP	room temperature
PSL-FSS_RCTEMP	reference cavity vacuum chamber temperature
PSL-FSS_MIXERM	mixer voltage monitor
PSL-FSS_SLOWM	slow actuator voltage monitor
PSL-FSS_VCOM	80 MHz VCO input monitor
PSL-FSS_TIDALINPUT	tidal actuator input

Table 17: Monitoring signals displayed on the FSS screen.

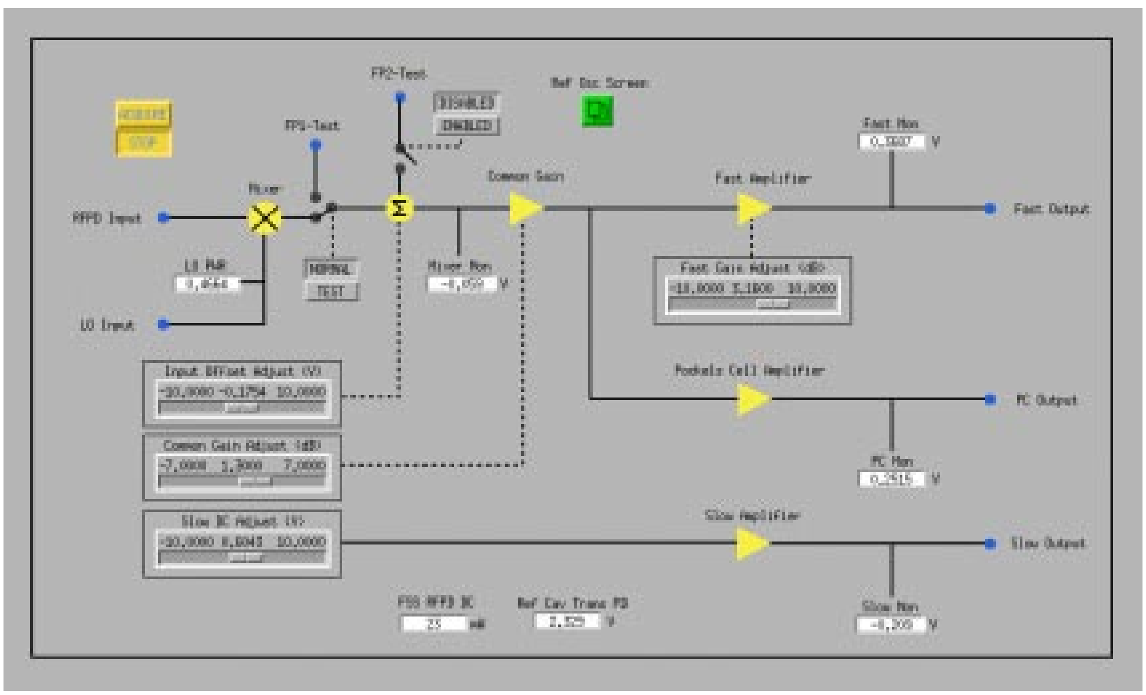

Figure 24: The FSS screen.

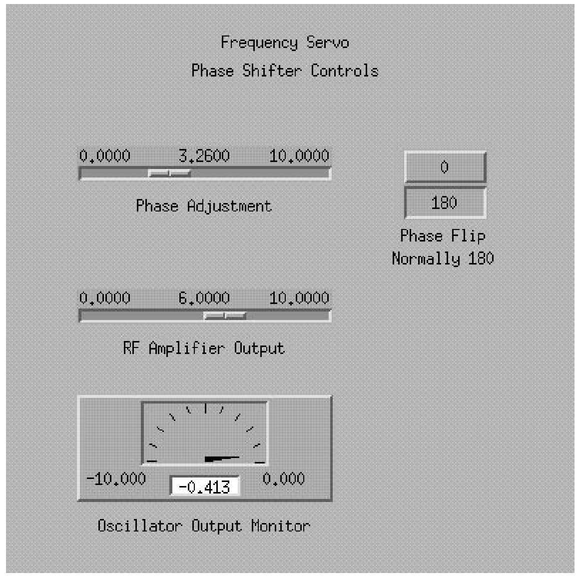

Figure 25: The Reference Oscillator screen.

12.3 The Reference Oscillator Screen

Figure 25 shows the Reference Oscillator screen for the frequency stabilization servo. Three adjustments are provided for: the phase adjustment, a 180 degree phase flip and the output of the rf amplifier. The phase adjustment adjusts the phase between the output of the rf photodetector and the local oscillator, to optimize the reflection locking discriminator signal. The 180 degree phase flip, corrects the sign of the feedback in case the laser locks onto a phase modulation sideband.

Generally, once adjusted this screen need not be adjusted again, unless the settings are no longer stored by the PSL input/output controller. Only the oscillator output is displayed as a monitor signal in the reference oscillator screen.

12.4 The VCO Screen

Figure 26 shows the VCO screen, which displays a slider to control the rf power output from the VCO to the frequency shifting AOM. Once adjusted during the PSL installation phase, this value need not be adjusted unless there has been some change to the optical components or the size of the laser beam. This slider is provided to optimize the diffraction efficiency of the frequency shifting AOM.

12.5 The PMC Screen

The PMC screen is similar in layout to the FSS screen and permits the user to control the PMC. Three slider controls are present on the screen. The "`Input Offset Adjust`" zeroes out any voltage offsets present in the mixer on the PMC servo card. The "`Servo Gain Adjust`" adjusts the gain of the servo and the "`Output DC Offset`" adjusts the voltage applied to the high voltage PZT at the end of the PMC, to vary the length of the PMC. Figure 27 shows the PMC screen.

The button labelled "`PMC Blank`" opens the loop and permits direct access to the PMC PZT. The "`ACQUIRE/STOP`" button activates the automated lock acquisition software. Normally this should be left in the "`ACQUIRE`" position, as the PMC will automatically re-acquire lock in the

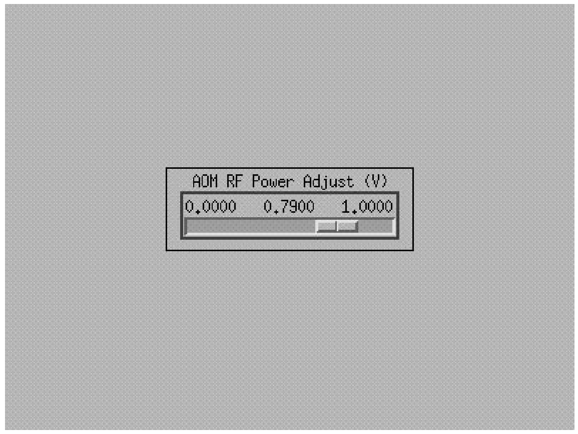

Figure 26: The VCO screen.

EPICS Name	Description
PSL-PMC_RFPDDC	35.5 MHz photodetector DC output
PSL-PMC_LODET	detected 35.5 MHz local oscillator output
PSL-PMC_PMCTRANSPD	PMC transmission
PSL-PMC_PCDRIVE	
PSL-PMC_PZT	PMC PZT voltage
PSL-PMC_MODET	35.5 MHz oscillator output power
PSL-PMC_PMCERR	servo error voltage

Table 18: Monitoring signals displayed on the PMC screen.

event of it losing lock. Should the user wish not to have the lock acquisition software active, for whatever reason, the "`STOP`" position should be depressed.

Table 18 tabulates the monitoring signals displayed on the PMC screen.

12.6 The ISS Screen

The ISS screen is used to operate the intensity stabilization servo. Two slider controls are provided: "`Intensity Servo Setpoint`" and "`Intensity Gain Adjust`". The "`Intensity Servo Setpoint`" controls the rf power applied to the intensity stabilization AOM. Varying the servo setpoint regulates the stabilized output power of the PSL. The "`Intensity Gain Adjust`" adjusts the gain of the intensity stabilization servo so that the PSL output meets the RIN requirements.

Another important control on the ISS screen is the "`AFTER MC / BEFORE MC`" button. This activates a switch on the intensity stabilization servo card which governs which photodetector the servo card takes its input from. As the button is depressed, the line drawing the input to the rest of the flow diagram animates to show which photodetector is the current active one.

12.7 On-line Help and Documentation

When written, the user screens will feature an on-line help facility. The documentation will guide the user in the controls of the PSL and will provide the schematics of the PSL electronics, mechanical drawings of the components and recorded values of past performance levels.

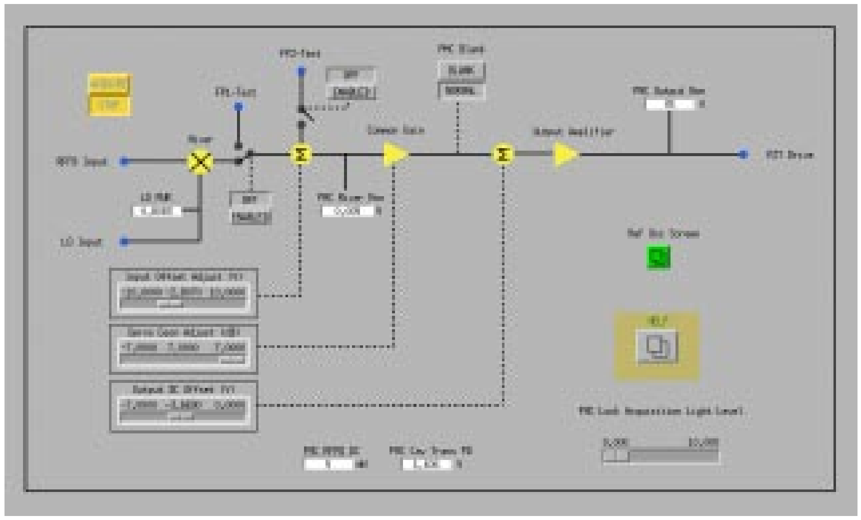

Figure 27: The PMC screen.

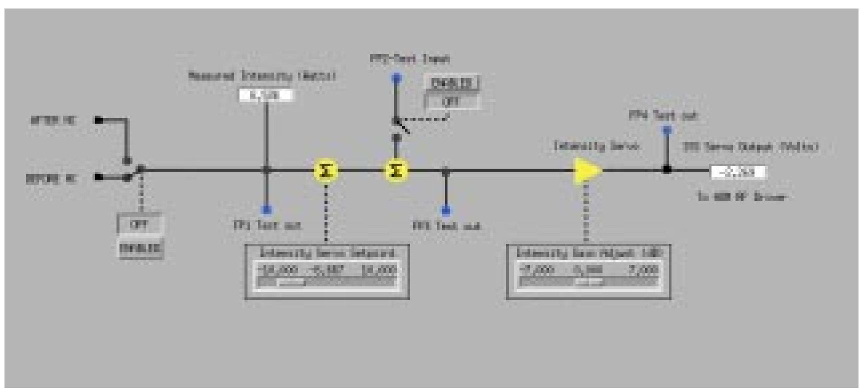

Figure 28: The ISS screen.

13 Performance Monitoring

Performance monitoring of the PSL is achieved via the EPICS archiving utilities AR and ARR. Table 19 lists the signals archived with the LHO 2k IFO PSL.

EPICS Name	Description
PSL-126MOPA_AMPMON	126 MOPA output power from the internal power monitor
PSL-126MOPA_126MON	NPRO output power from the internal power monitor
PSL-126MOPA_DS1	diode monitor 1
PSL-126MOPA_DS2	diode monitor 2
PSL-126MOPA_DS3	diode monitor 3
PSL-126MOPA_DS4	diode monitor 4
PSL-126MOPA_DS5	diode monitor 5
PSL-126MOPA_DS6	diode monitor 6
PSL-126MOPA_DS7	diode monitor 7
PSL-126MOPA_DS8	diode monitor 8
PSL-126MOPA_HTEMP	head temperature
PSL-FSS_RFPDDC	reference cavity "visibility"
PSL-FSS_LODET	frequency servo local oscillator power
PSL-FSS_PCDET	EOM drive
PSL-FSS_FAST	fast voltage monitor
PSL-FSS_PCDRIVE	EOM voltage monitor
PSL-FSS_RCTRANSPD	reference cavity transmission monitor
PSL-ISS_AOMRF	rf drive to the intensity stabilization AOM
PSL-PMC_RFPDDC	PMC "visibility"
PSL-PMC_LODET	PMC servo local oscillator power
PSL-PMC_PMCTRANSPD	PMC transmission monitor
PSL-PMC_PCDRIVE	35.5 MHz oscillator
PSL-PMC_PZT	high voltage drive to the PMC PZT
PSL-FSS_MODET	21.5 MHz oscillator output power monitor
PSL-PMC_MODET	35.5 MHz oscillator output power monitor
PSL-FSS_MINCOIN	
PSL-FSS_MINCOOUT	
PSL-FSS_RMTEMP	IOO / PSL optical table enclosure temperature
PSL-FSS_RCTEMP	reference cavity temperature
PSL-FSS_MIXERM	frequency servo mixer monitor
PSL-FSS_SLOWM	slow voltage monitor
PSL-ISS_ISERR	intensity servo error point
PSL-PMC_PMCERR	PMC servo error point

Table 19: Signals archived by ARR.

14 Lock Acquisition

Automated lock acquisition has been demonstrated for the frequency stabilization and PMC servos. Other PSL servos always have an error signal present and so lock acquisition is not an issue. The order in which the servos acquire lock was found to be important. It was found that the frequency stabilization servo should be locked prior to attempting to lock the PMC servo. This is due to the nature of the PMC. The PMC, which must stay resonant with the incident light, has an easier job if there are no large frequency excursions to deal with during the lock acquisition phase.

14.1 Frequency Stabilization Servo Lock Acquisition

At the time of writing, the frequency servo lock acquisition code is not fully developed. One problem is that the frequency servo needs to be locked manually once so that the gain settings can be noted and entered into the lock acquisition code. This is done during the installation phase of the PSL. Currently the software does not automatically adjust the servo gains for the installation phase.

When started the lock acquisition software sets the slow voltage to be zero. This places the laser in the middle of a mode-hop-free region by default, since this is the way the laser is adjusted at Lightwave Electronics Inc. The fast gain is adjusted to some intermediate value and the common gain is set to a small value above zero. The slow voltage is then increased and the transmission through the reference cavity is monitored. When the transmission of the reference cavity reaches a level consistent with a TEM_{00} mode being resonant in the cavity, the slow voltage ramp ceases. At this point an error signal is established and the servo acquires lock.

Once lock has been acquired the fast and common gains are adjusted to their operational values. The voltage applied to the phase correcting EOM is then inspected. If this voltage is railed at either -10 V or 10 V, the slow voltage is adjusted so that this is no longer the case. At this stage the frequency stabilization servo is locked.

From an initial start, the whole lock acquisition sequence can take a period of some minutes (approximately 3 minutes). The sluggish response of this is dominated by the slow response of the slow actuator, which has three poles at 0.2 Hz. Blockages of the beam caused by objects being accidentally placed in the beam cause the servo to lose lock for the period of time that the obstruction is in the beam. Once the obstruction is removed, lock has always been re-acquired within a few seconds.

14.2 PMC Servo Lock Acquisition

The lock acquisition software, when activated by the "`ACQUIRE / STOP`" button enables the "`FP-1`" input switch and the "`PMC BLANK`" switch. The voltage applied to the PZT is then increased until the transmission of the PMC reaches a level consistent with the TEM_{00} mode being resonant in the PMC. The "`PMC BLANK`" and "`FP-1`" switches are then disabled and the servo loop is closed. The servo gain is then adjusted for optimum performance.

By contrast to the frequency stabilization servo, the PMC servo has a much faster response and takes approximately one minute to acquire lock.

15 Hardware Implementation

PSL-related electronics are housed in a CDS electronics rack (see Table 20 for designations) located within the appropriate laser area enclosure. The rack houses a VME crate, a Eurocard cage, the Lightwave Electronics Inc. 126 MOPA Laser power supply and other power supplies required for other PSL items. The VME-bus based modules are listed in Table 21.

Inteferometer	Designation
2k	2X7
4k	1X3

Table 20: PSL electronics rack designations.

Module Name	Description	Manufacturer	Base Address
Baja4700	input / output controller	Heurikon	0x1F04
VMIVME 3113A	12-bit analog input board	VMIC	0xFF2000
VMIVME 3123	16-bit analog input board	VMIC	0xFF2C00
VMIVME 4116	digital-to-analog converter	VMIC	0xFF5C00
VMIVME 4116	digital-to-analog converter	VMIC	0xFF5D00
VMIVME 4116	digital-to-analog converter	VMIC	0xFF5E00
XY212	binary input board	Xycom	0xFFA000
XY220	binary output board	Xycom	0xFFC800

Table 21: The PSL VME-bus modules.

16 PSL Diagnostics

All the PSL control servos contain test inputs and monitoring points that permit an analysis of both the open and closed loop performance.

17 External Diagnostic Modes of the PSL

The topic of interferometer diagnostics is not well developed at the time of writing and as a result, the external diagnostic modes of the PSL have not been fully defined. Some of the diagnostic modes mentioned in *(Infrared) Pre-stabilized Laser (PSL) Conceptual Design* **LIGO T970087–04–D** seem to be over specified, making the their implementation extremely difficult.

All the intensity modulation related diagnostic modes should be able implemented with the intensity stabilization AOM. These modes include:

- Beam Finding Mode
- Cavity Ringdown Mode
- System Diagnostics Mode
- Calibrated Power Reduction Mode

17.1 Beam Finding Mode

In beam finding mode, the output power of the PSL was to be square-wave modulated by up to 50 % at a frequency of 2 Hz, with the intensity stabilization and frequency stabilization loops remaining active. Whilst it is not clear how this diagnostic mode can be implemented, one possible solution is to use a mechanical chopper to chop the output of the PSL.

17.2 Cavity Ringdown Mode

Cavity ringdown mode is used to measure the ringdown times of the various optical cavities in the interferometers. The requirements for this diagnostic have not been finalized. Implementation is expected to be via the intensity stabilization AOM.

17.3 System Diagnostics Mode

To perform system-level signal diagnostics, the PSL allows both output power modulation and frequency modulation. Implementation of the output power modulation is expected to be via the intensity stabilization AOM, frequency modulation is expected to be via the VCO input driving the frequency shifter.

17.4 Calibrated Power Reduction Mode

Calibrated power reduction mode allows the output of the PSL to be reduced from full power to 10 mW in a calibrated manner. The best way to implement this mode has not been determined at the time of writing.