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

	LIGO-T950030-03	**-D**	5/25/95
Document Type	*Doc Number*	*Group-Id*	*Date*

Prestabilized Laser Design Requirements

Title

Jordan Camp

Authors(s

DRAFT

This is an internal working note
of the LIGO Project

California Institute of Technology
LIGO Project - MS 102-33
Pasadena CA 91125
Phone (818) 395-2966
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu
WWW: http://www.ligo.caltech.edu

1.0 Introduction

The prestabilized laser (PSL) subsystem of the LIGO interferometer provides an independent source of light prestabilized in frequency. The PSL output is directed to the input optics (part of the Input/Output Optics (IOO) subsystem), where additional stabilization in power, frequency and beam pointing is applied. The light is then injected into the interferometer core optics. Feedback to the PSL is obtained from both the input optics and Length Sensing and Control (LSC) (see Figure 1).

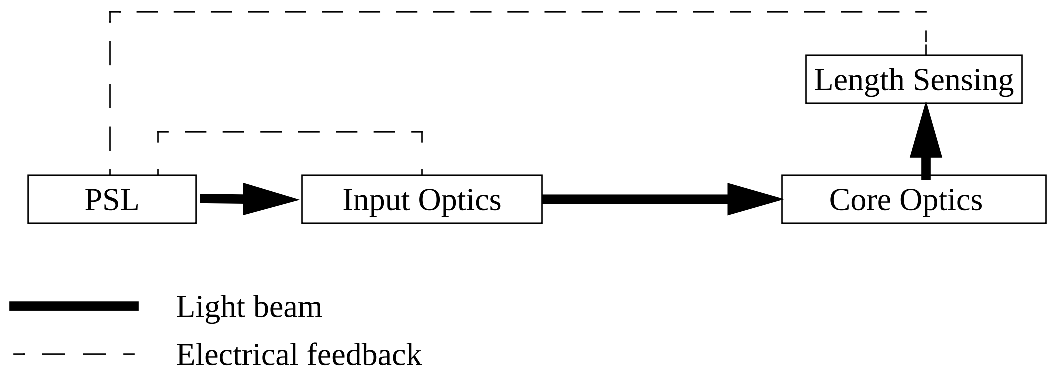

FIGURE 1. PSL Subsystem

1.1 Purpose and Scope

This document establishes the PSL design requirements and addresses the following topics:

1. Introduction
2. LIGO primary requirements relevant to the PSL design
3. PSL definition
4. PSL design requirements
5. PSL interfaces
6. PSL conceptual design
7. PSL diagnostics
8. PSL testing to demonstrate compliance with requirements
9. PSL safety

2.0 LIGO primary requirements

The following LIGO primary requirements lead to PSL design requirements:

- Initial detector shot noise strain equivalent at arm knee frequency: 1.3×10^{-23} /$Hz^{1/2}$ at 90 Hz[1]
- availability: 75% for triple coincidence operation, 85% for double coincidence, 90% for singles operations[2]
- Minimum continuous operation time: 40 hrs.[3]
- Maximum background pulse rate per interferometer: 1 per minute[4]

3.0 PSL definition

The PSL subsystem includes the following elements:

- Modified argon ion laser with power supply and heat exchanger
- Frequency servo including electrooptic and PZT actuators, reference and RF photodiodes sensor, mode matching lenses, and reference cavity (including vacuum enclosure and seismic isolation stacks).
- Intensity servo including acousto-optical modulator and photodiode sensor.
- Optical components including beam splitter, steering mirrors, Faraday isolators, polarizers, quarter and half-wave plates
- Environmental control including dust enclosure, nitrogen gas purge and reference cavity temperature stabilizer
- Optical tables for the above

It does *not* include:

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

1. LIGO Science Requirements Document, LIGO-E950018-00-E, pg. 9
2. Ibid, pg. 12
3. Ibid, pg. 12
4. Ibid, pg.

4.0 PSL design requirements

4.1 Peformance Requirements

The LIGO primary requirements yield requirements on the light entering the core optics. These *requirements* may be satisfied with an interplay of *specifications* on the PSL and input optics subsystems. The following diagram (Figure 2) identifies the locations and configurations at which the light specifications are made:

(a) the PSL output

(b) the input optics output (with feedback from the input optics to the PSL)

(c) the core optics input (with additional feedback from Length Sensing to the PSL)

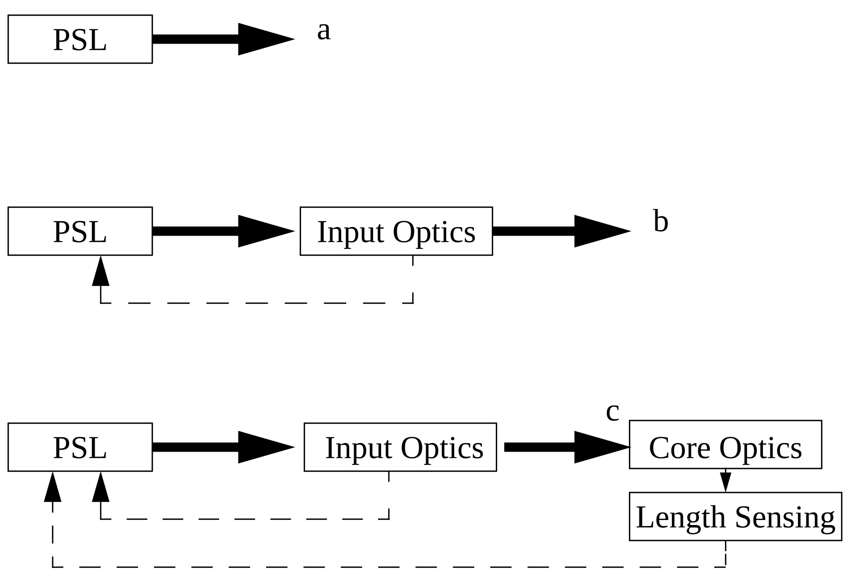

FIGURE 2. Locations and configurations for light specifications

The following table (Table I) lists specifications on the light at the locations identified in Figure 2.

Table 1: Light Specifications (TBR)

	Power (watts)	**Frequency noise** $\tilde{\upsilon}(f)$ (Hz/Hz$^{1/2}$)		**Beam jitter** $\tilde{\varepsilon}_1(f)/\varepsilon_0$ (1/Hz$^{1/2}$)	**Intensity noise** $\tilde{I}(f)/I$ (1/Hz$^{1/2}$)		**Polarization noise** $\tilde{A}_H(f)/A_V$ (1/Hz$^{1/2}$)
		90 Hz	10 kHz	90 Hz	90 Hz	10 kHz	90 Hz
PSL (a)	4	$1x10^{0}$	$3x10^{-2}$	$2x10^{-4}$	$1x10^{-4}$	$2x10^{-6}$	$1x10^{-6}$
Input optics (b)	2.5	$1x10^{-3}$	$2x10^{-4}$	$3x10^{-7}$	$1x10^{-7}$	$2x10^{-7}$	TBD
Core optics (c)	2.5	$2x10^{-6}$	$2x10^{-4}$	$3x10^{-7}$	$1x10^{-7}$	$2x10^{-7}$	TBD
LIGO require-ments	2.5	$2x10^{-6}$	$3x10^{-4}$	TBD	$2x10^{-6}$	$2x10^{-4}$	TBD

These specifications, which are taken as a ‘shared solution’ to satisfying the LIGO requirements, are consistent with the current PSL prototype performance and expected performance of the input optics and LSC subsystems. The table also lists the LIGO requirements (derived in the appendix).

The following sections expand on the table entries above. Details are given in the appendix.

4.1.1 Power

The laser power entering the core optics must be such that the shot noise contribution N_s to the interferometer spectral noise density $\tilde{h}(f) \le 1.3\ x\ 10^{-23}$ /Hz$^{1/2}$ at 90 Hz. This requires 2.5 watts power. The input optics will transmit ~65 % of the incident power, leaving a specification of 4 watt PSL output.

4.1.2 Frequency noise

Frequency noise $\tilde{\upsilon}(f)$ at the interferometer arms must be such that the induced strain noise is <10% of N_s, the shot noise limited strain sensitivity. This yields a LIGO requirement of $\tilde{\upsilon}(90\ Hz) \le 2\ x\ 10^{-6}$ Hz/Hz$^{1/2}$ and $\tilde{\upsilon}(10\ kHz) \le 3\ x\ 10^{-4}$ Hz/Hz$^{1/2}$. This can be achieved with expected servo gains and the PSL prototype specification of $\tilde{\upsilon}(90\ Hz) \le 1\ x\ 10^{0}$ Hz/Hz$^{1/2}$ and $\tilde{\upsilon}(10\ kHz) \le 3\ x\ 10^{-2}$ Hz/Hz$^{1/2}$ (The prototype frequency noise spectrum falls to ~ 0.1 Hz/Hz$^{1/2}$ at 1 kHz and then slowly decreases towards higher frequencies).

4.1.3 Beam jitter

Beam jitter (expressed as the time-varying ratio $\tilde{\varepsilon}_1(f)/\varepsilon_0$ of the amplitude of the 1st higher and zeroth order Gaussian beam modes) produces strain noise by causing frequency noise in the interferometer arms. The LIGO requirements are TBD. (The prototype jitter noise spectrum falls sharply above 100 Hz, to < $10^{-6}/\mathrm{Hz}^{1/2}$ at 1.5 kHz.)

4.1.4 Intensity noise

$\tilde{I}(f)$ couples to strain noise through an rms deviation $(\Delta x)_{\mathrm{RMS}}$ from exact cavity resonance. This gives a LIGO requirement of $\tilde{I}(90\ Hz)/I \le 2\ x\ 10^{-6}\ /\ \mathrm{Hz}^{1/2}$, which is achieved with the PSL prototype specification and intensity stabilization after the mode cleaner. (The prototype intensity noise spectrum falls to ~ $10^{-5}\ /\mathrm{Hz}^{1/2}$ at 1 kHz and then falls as 1/f towards higher frequencies).

4.1.5 Polarization noise

Polarization noise is expressed as the time-varying ratio $\tilde{A}_H(f)/A_V$ of the amplitude of horizontal and vertical polarization of the light. The LIGO requirements are TBD.

4.2 Functional Requirements

4.2.1 Availability

The PSL availability (*A*) is specified to be *A* > 95%. This value meets the LIGO availability primary requirement (pg. 4) and leaves margin for the interferometer subsystems which require prestabilized light to become operational.

5.0 PSL Interfaces

5.1 Optical

The PSL delivers light to the input optics. The physical location of the interface is the set of steering mirrors at the start of the input optics chain which steer the beam between the subsystems. The output beam height is nominal 1 m, and will be compatible with the input optics beam height.

5.2 Signal

- The PSL will provide a lock status signal to the IOO, Alignment Sensing and Control (ASC) and LSC subsystems.
- The PSL will receive frequency correction signals from the IOO and LSC and intensity feedback from IOO.

5.3 Facility

The vibration and acoustic noise requirements on the LIGO facility are detailed elsewhere.[1] The following requirements are placed on the facility:

- Electric power (per laser): Laser- 480 V 3 phase, 90 A; Heat exchanger - 208 V, 7.1 A. The laser power supply must be < 3.7 m (12 ft) from the laser head, and < 3.7 m (12 ft) from the switch box
- Plant water (per laser): quality: tapwater or distilled water allowed, no deionized or seawater; static pressure: 2.1-6.9 x 10^5 Pa (30-100 PSI); temperature: 5 - 25 °C; flow rate: 38-56 liter/min (10 -15 GPM)
- Ambient temperature variation in region of PSL: +/- 4 °C. (This number is derived by considering the maximium length change in the laser and reference cavity that can be accomodated by the range of the laser slow PZT.)
- Space requirement: the PSL subsystem, including optical table, and electronics racks, will comprise a volume of ~ 4 ft x 12 ft x 8 in
- Lift capability: a crane shall be avialable to move the PSL optical tables as necessary.

5.4 CDS

The PSL electronic and controls interface is the Control and Data System (CDS) [2]. CDS provides the electronics to control the laser, its associated servo loops, and all related electronic components. The CDS interface will perform the following functions:

- Control of laser, including tube current, argon refill, and water cooling

1. Vibrational and Acoustic Requirements for the LIGO facilities, LIGO-L950238
2. Prestabilized Laser Controls, LIGO T950001-1-C

- Control of PSL electronic modules, including status, gain, dc offset
- Control of reference cavity, including vacuum level and temperature stabilization
- Data acquisition of relevant signals
- Monitoring and recording of signals which indicate proper PSL functioning

6.0 PSL conceptual design

Figure 3 shows a block diagram of the PSL, including the laser, frequency and power stabilization loops, RF phase modulation, ringdown apparatus and optical isolation.

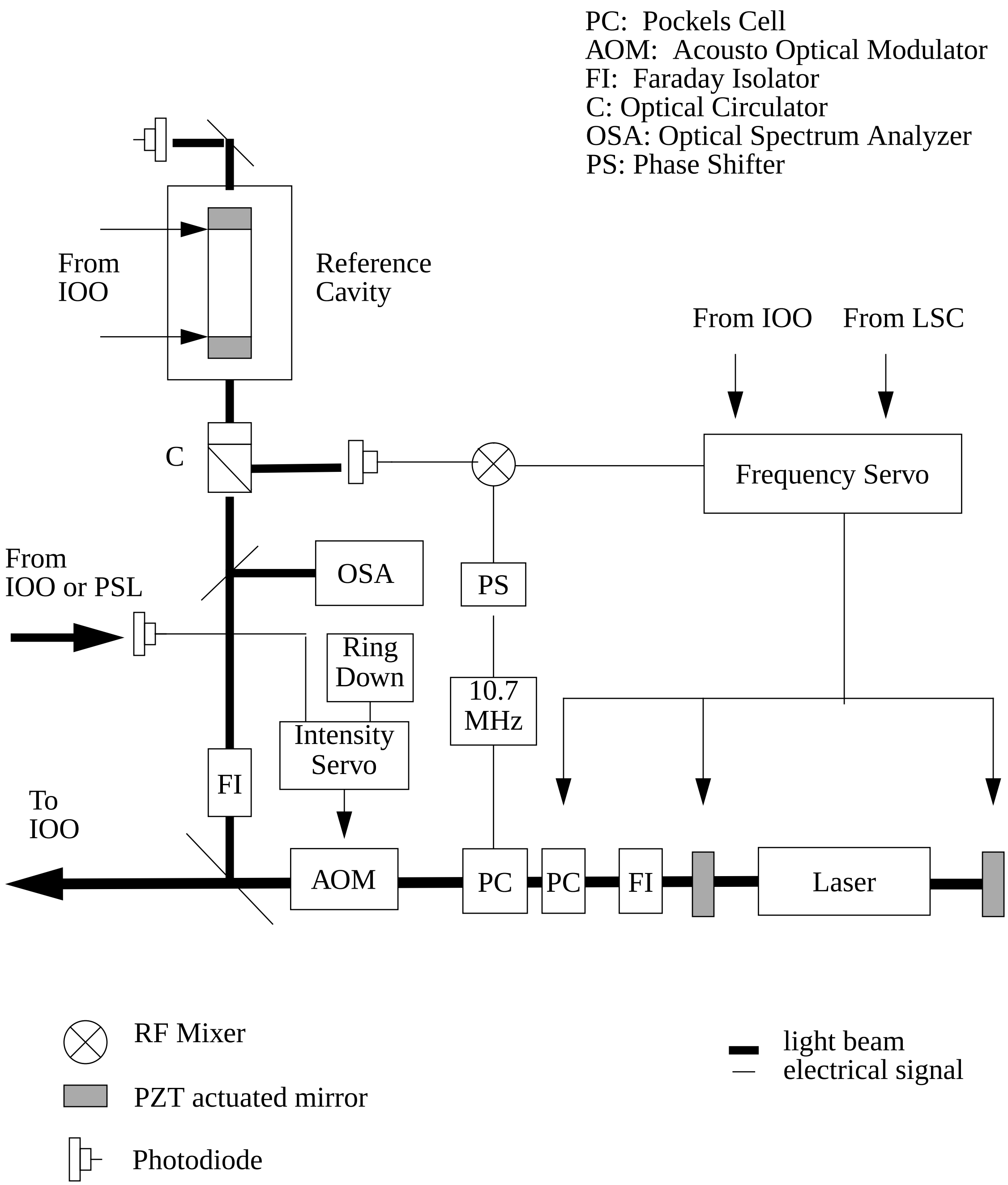

FIGURE 3. PSL block diagram

6.1 Conceptual Design: Physical Layout

The laser and associated optical components are located on a set of optical tables. Additional components located near the tables include a supply of clean, dry nitrogen, laser power supply and heat exchanger. A set of PZT actuated steering mirrors are located < 1 m from the reference cavity. The optical table will be enclosed and nitrogen-purged to keep dust away from the components.

6.2 Conceptual Design: Performance Requirements

The following relates the PSL conceptual design to the performance requirements.

6.2.1 Power

A commercial argon ion laser provides >10 watts power in single line, multiple frequency. The use of an etalon restricts the laser output to >5 watts of power at a single frequency and single transverse mode. Optical losses due to the sum of the PSL optical components leave >4 W delivered to the input optics.

6.2.2 Frequency Noise

The laser is modified so that the mirrors forming its resonant cavity are decoupled from the laser tube. The laser tube is isolated from the laser table with a set of mass/elastomer spring stacks. The mirrors are held on separate mounts on an isolated super-invar breadboard and coupled to PZT actuators. Together with 2 phase correcting Pockels cells they form a set of actuators which control the laser frequency.

A final RF Pockels cell appends sidebands to the light. Several per cent of the light is picked off and directed to the reference cavity, a 1 m optical resonator composed of two high reflectance mirrors held on a rigid quartz spacer which is vibration isolated and held under vacuum. Its resonant frequency provides the reference for stabilization of the laser frequency to the specified performance level through feedback to the frequency actuators.

6.2.3 Beam Jitter

Decoupling of the mirrors from the laser body leave the output beam jitter (at location (a)) within the design specification. No active stabilization is required within the PSL.

6.2.4 Intensity Noise

A reference photodiode located after the mode cleaner (IOO subsystem) measures ~1 mW of the light intensity; this is then compared to a fixed reference level. Feedback is directed to an acousto-optical intensity modulator which stabilizes the light intensity.

6.2.5 Polarization Noise

No active measure is required to suppress the specified level of polarization noise.

6.3 Conceptual Design: Functional Requirements

6.3.1 Availabilty

The PSL availability will be affected by any mechanism which causes the PSL performance to drop below its requirements. The following is a list of known mechanisms and the conceptual design to limit their effects and keep the availability at the required level.

- Laser system failure: numerous types of component malfunctions may cause the laser to fail, including problems with power supply electronics, temperature and water flow sensors, etc. To prevent excessive downtime, each PSL subsystem will have a standby laser (located near the primary) which can be quickly switched on in the case of a primary failure. An on-site service area will be used for diagnosis and repair.
- Laser tube replacement: the laser has a waranteed lifetime of 2000 hrs., with a typical expectancy of 4000 hrs. Tube replacement and associated alignment takes about 8 hrs. and is accomplished in situ during a maintenance period or at the service area.
- Thermal drift: temperature variations in the facility will cause length changes in the laser and reference cavities. The changes are minimized by mounting the laser mirrors on a superinvar breadboard and using a quartz spacer for the reference cavity. Active temperature stabilization of the reference cavity will be performed at the level of ~0.1 $°$C. The laser PZT-actuated mirrors dynamic range is provided to the frequency servo to keep the laser locked to the reference cavity.
- Mirror losses: the accumulation of foreign material on the mirror surfaces causes a deterioration of the mirror performance. Accumulation is limited by a gas purge of the optical surfaces at 1 atm and a vacuum bakeout of the reference cavity.
- Alignment: drift of the alignment of the reference cavity with respect to the input beam caused by thermal variation results in fluctuations in visibility. The alignment may be adjusted with PZT actuated steering mirrors as part of routine daily maintenance.
- Laser tube gas fill: the laser tube is replenished with argon gas typically several times a day. The fill cycle duration is on the order of 1 min, and may be done as part of routine daily maintenance.

7.0 PSL Diagnostics

7.1 Diagnostics within the PSL

The following diagnostics will be implemented within the PSL:

- Test inputs and output monitors will be available on the frequency and intensity servos for measurements of sensor and actuator levels, and total and electronic loop gains in closed loop operation[1].
- An optical spectrum analyzer will verify that the laser is operating in a single longitudinal mode and will measure the modulation sidebands.
- Ringdowns will measure the reference cavity storage time.
- Shot noise will be monitored with the use of an incandesent light fixed to the RF photodiode.
- The plasma tube voltage and current will be monitored to warn of an impending tube failure.

7.2 PSL used as a diagnostic for other subsystems

The PSL electronics will allow for dithering of frequency, intensity to diagnose the performance of other subsystems. A ringdown mode of operation will provide storage time measurements of the IOO and Core Optics cavities.

8.0 PSL Testing

8.1 Prototype

A prototype of the PSL using CDS controls and electronics will be tested in the optics lab over a 2 month period. It will then be moved to the 40 m laboratory where further experience will be gained in its usage.

8.1.1 Availability Testing

The Availability test will run the PSL full time to simulate the LIGO PSL operation. The following quantities will be logged continuously so that the requirement of 95% availability is tested:

- Power
- Visibility (measure of alignment of light with reference cavity)

The LIGO primary requirement of 1 background pulse/minute presents a stringent requirement on PSL transients. The following quantities will be logged continuously to investigate transient behavior:

1. Prestabilzed Laser Controls, LIGO T950001-1-C

- Servo signals including frequency and intensity servo error signals, and sensor and actuator signals
- Power supply levels

The following quantities will be measured periodically during the testing period:

- Frequency noise spectral density: measured with an independent optical cavity operating outside the frequency stabilization loop
- Intensity noise spectral density: measured with a reference photodiode outside the intensity stabilization loop
- Beam jitter spectral density: measured with a quadrant photodiode

8.1.2 40 m Lab Testing

Operation of the PSL prototype at the 40 m lab will test the performance of the PSL over extended time periods, including:

- Availability
- Laser frequency stabilization at the quiet levels of the 40 m cavities (~ 10000 times quieter than the reference cavity)

8.2 Qualification

Criteria for qualification tests for 1st article will be determined during the final design.

8.3 Acceptance

Criteria for acceptance tests for production articles will be determined during the final design.

9.0 PSL Safety

All aspects of the PSL operation will be conducted in a way consistent with ANSI standard safety practices. The following is a partial list of safety concerns:

- Insulation of high voltages
- High gas and water pressures
- Containment of stray light beams
- Secure mechanical fixtures for all components
- Procedures to guarantee safety during PSL operation and service.

Appendix

The following parameters are assumed for the LIGO interferometer:

Arms:[1]

Input mirror: T=3%, A= 100 ppm, R= (flat)

Far mirror: T=10 ppm, A= 100 ppm, R= 6 km

Storage time: τ_s = 8.8 x 10^{-4} sec

Cavity pole frequency: f_0 = 90 Hz

Cavity finesse: F = 208

Cavity length: L=4 km

Recycling cavity:[2]

Length: 12 m

Recycling mirror: T=3%, A=100 ppm, R= (flat)

Recycling factor: G_r=30

12 m mode cleaner:[3]

Input/output mirror transmission: T=2000 ppm

Far high reflectance mirror: R= 17 m

Cavity length: L= 12 m

Laser light:[4]

Wavelength: λ = 5.14 x 10^{-7} m

Photodiode quantum efficiency: η = 0.8

---

1. R. Weiss, Basis of the Optical Wavefront Specifications, Document Number TBD
2. Ibid
3. A. Abromovici, Input Optics: Conceptual Design, Document Number TBD
4. R. Weiss, Basis of the Optical Wavefront Specifications, Document Number TBD

The following material expands on the entries in table 2.1

1) Laser Power[1]

$$\tilde{h}(f) = \left(\frac{L}{16\pi D}\right)\left(\frac{2hc\lambda}{\eta P G_r}\right)^{1/2}\left[1+\left(\frac{f}{f_0}\right)^2\right]^{1/2}$$

where L is the total of transmission, scattering and absorption losses for a cavity arm, D is the arm length, and ηP is the efficiency corrected power incident on the recycling mirror.

With $\tilde{h}(90\ Hz)$ = 1.3 x $10^{-23}/\mathrm{Hz}^{1/2}$, we have P ~ 2.5 W.

Determination of the required PSL output uses the value of 65 % for the input optics optical efficiency. This value is taken as the product of 4 factors[2]:

mode matching: 95 %

efficiency of (post mode cleaner) Faraday isolator: 90 %

efficiency of FSSC: 80%[3]

efficiency of remaining optics: 95 %

2) Frequency noise

$\tilde{\upsilon}(f)$ couples to strain noise $\tilde{h}(f)$ through a mismatch in the cavity arms storage time $\Delta\tau$. We have: $\tilde{h}(f) = \left(\frac{\tilde{\upsilon}(f)}{\upsilon}\right)\left(\frac{\Delta\tau}{\tau}\right) T\, R(f)$

where T is the frequency noise suppression resulting from a software subtraction and the function *R(f)* contains the filtering action of the recycling cavity. *R(f)* may be obtained the following way:

Consider a coupled cavity composed of a recycling mirror and a LIGO arm, with A the frequency spectrum of the light at the recycling mirror input, B the spectrum at the arm input, and C the spectrum at the arm output. The ratio C/B has a pole at 90 Hz; C/A has a pole at 2 Hz; therefore B/A (or *R(f)*) has a pole at 2 Hz and a zero at 90 Hz.

Thus *R(f)* = (2 x sqrt(2)/90) f=90 Hz

= (2/90) f=10 kHz

1. LIGO ICD handbook, v 2.0, p. 4, Document Number TBD
2. A. Abromovici, Input Optics Conceptual Design, Document Number TBD
3. D. Shoemaker, private communication

We may then write

$$\tilde{\upsilon}(f) = S\,\tilde{h}(f)\,\upsilon\left(1/\left(\left(\frac{\Delta\tau}{\tau}\right)T\,R(f)\right)\right)$$

where S is the imposed design margin to limit the contribution of frequency noise to the total noise budget. With

S = 10 %

$\frac{\Delta\tau}{\tau} \sim 0.01$

$\tilde{h}(f) = N_s$ (shot noise limited sensitivity at 90 Hz) = 1.3 x 10^{-23}/$Hz^{1/2}$ and T = 1 (a conservative choice)

we obtain $\tilde{\upsilon}(90\ Hz) = 2 \times 10^{-6}$ Hz/$Hz^{1/2}$ and $\tilde{\upsilon}(10\ kHz) = 3 \times 10^{-4}$ Hz/$Hz^{1/2}$ for the LIGO primary requirements.

The LIGO arms are the most stable frequency references above ~ 100 Hz and will provide feedback to stabilize the laser at this level. Present planning is to have a gain of >60 dB at 90 Hz, and a gain of 0 dB at 10 kHz.[1] This leaves the requirement of $\tilde{\upsilon}(90\ Hz) = 2 \times 10^{-3}$ Hz/$Hz^{1/2}$ and $\tilde{\upsilon}(10\ kHz) = 3 \times 10^{-4}$ Hz/$Hz^{1/2}$ at the output of the input optics subsystem (configuration (b)). These values are within the expected mode cleaner performance[2], listed in Table I.

Finally, the mode cleaner will provide feedback to the PSL to stabilize the laser at this intermediate level. Present planning is to have a gain > 60 dB at 90 Hz and > 40 dB at 10 kHz.[3] This is consistent with the PSL prototype frequency noise specification.

3) Beam jitter

The frequency noise in a locked cavity from the presence of the Nth order transverse mode with static misalignment term ε_0 and fluctuating spectral density $\varepsilon_N(f)$ has been calculated (but not yet experimentally verified):[4]

---

1. LIGO recycled interferometer servo design update, L. Sievers, 3/94, Document Number TBD
2. A. Abromovici, An Improved Mode Cleaner for the 40 m Prototype, May 1991, Document Number TBD
3. Ibid
4. A. Abromovici, Do Wiggle Effects Depend on Mode Cleaner Length, Oct 1988, Document Number TBD.

$$\tilde{\upsilon}(f) = \frac{\pi c}{2LF^2} \frac{\tilde{\varepsilon}_N(f)\varepsilon_0 \sin N\varphi}{1 + r_1 r_2 - 2\sqrt{r_1 r_2}\cos N\varphi}$$

where $\cos\left(\frac{\phi}{2}\right) = \sqrt{\left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right)}$

with r,R: mirror reflectivity, curvature and L the cavity length. We have $\phi_{arm} = 1.91$ and take $\varepsilon_0 = 0.3$ (corresponding to ~10% of the light coupled into the higher order mode.)

Beam jitter suppression is obtained by passing the light through the mode cleaner. The suppression factor for the first higher order transverse mode is:

$S_1 = \frac{2\sqrt{r}}{1-r} \sin\frac{\phi_{MC}}{2}$ ~ 800 for the mode cleaner parameters listed above.

The LIGO requirements are TBD.

4) Intensity noise

We have: $\tilde{h}(f) = \frac{\Delta x}{L} \frac{\tilde{I}(f)}{I} R(f)$, where

Δx is the rms deviation from resonance, L is the cavity length and *R(f)* is the filtering factor from the recycling cavity (described in (2) above).

We then have: $\frac{\tilde{I}(f)}{I} = S\,\tilde{h}(f)\left(1 \big/ \left(\frac{\Delta x}{L} R(f)\right)\right)$

where S is the imposed safety margin for the allowed contribution of intensity noise to the total noise budget.

The value of Δx measured at the 40 m laboratory is 1 x 10^{-13} m; this is taken as a conservative value for LIGO.

With $\tilde{h}(f)$ = N_s (shot noise limited sensitivity) = 1.3 x 10^{-23} /$Hz^{1/2}$ at 90 Hz, and S = 0.1, we have $\tilde{I}(90\ Hz)/I$ = 2 x 10^{-6}/ $Hz^{1/2}$ and $\tilde{I}(10\ kHz)/I$ = 2 x 10^{-4}/ $Hz^{1/2}$ for the LIGO requirements. This level of intensity noise requires intensity stabilization after the mode cleaner; it is consistent with expected servo gains of 80 dB at 90 Hz and 20 dB at 10 kHz and the PSL intensity noise and beam jitter specifications.

Finally, intensity noise at the PSL output will also give rise to frequency noise at the mode cleaner. The frequency stability requirement of the mode cleaner requires $\tilde{I}(90\ Hz)/I = 2 \times 10^{-4}/\mathrm{Hz}^{1/2}$ at the PSL output (configuration (a)), which is met by the PSL prototype specification.