LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Pre-Stabilized Laser Design Requirements

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1 Introduction

1.1 Purpose and general description

The purpose of this document is to define the content of the Advanced LIGO (aLIGO) Pre-Stabilized Laser subsystem (PSL), and to give the design requirements for the PSL. The PSL subsystem provides the laser radiation for the LIGO interferometers. The heart of the PSL is the aLIGO Laser being developed by Laser Zentrum Hannover (LZH). The goal of the PSL development work is to design a system capable of accommodating the aLIGO Laser and reducing its output beam frequency and power fluctuations as well as spatial impurities to the levels required for the aLIGO detectors. The PSL subsystem will be capable of remote control and monitoring via computer and will incorporate internal diagnostics. Detector availability considerations require that the PSL subsystem acquires lock quickly and reliably and operates without loss of lock for long periods of time. In addition, the PSL must maintain performance while accommodating control signals from the IOO and LSC subsystems that enable other subsystems to achieve required performance. Furthermore the PSL has to be able to operate in a commissioning mode with reduced power and reduced stability requirements.

Designing and fabricating the laser systems with the reliability and maintainability required to enable the detectors to meet availability goals is expected to present a major challenge for the PSL subsystem.

1.2 Scope

The PSL provides the pre-stabilized laser light for the interferometer, via its interface with the Input Optics (IO) subsystem. The PSL includes:

- The high power laser, delivering light to the IO according to the requirements given below. The cooling system for the high power laser is part of the PSL.
- Systems for stabilizing the laser frequency and power to the levels stated below. The PSL *is not* responsible for providing the final level of frequency stability required by the interferometer, only the first, or ‘pre-stabilization’ level. The PSL *is* responsible for providing the final level of power stability required by the interferometer.
- The optical table that holds the PSL and those components of the IO that lie between the PSL output and the point of beam injection into the vacuum system. The optical table support and the exact positioning of the table within the LVEA coordinate system is not part of the PSL scope.
- Wideband actuation of the laser frequency, to enable additional levels of frequency stabilization.
- Diagnostics and supervisory controls functions, compatible with the CDS systems; provision of appropriate signals to the interferometer data acquisition (DAQ) system.
- The PSL has to provide a beam with at least 5mW power (in the PSL low power mode) for the arm-length-stabilization system (ALS) downstream of the reference cavity.

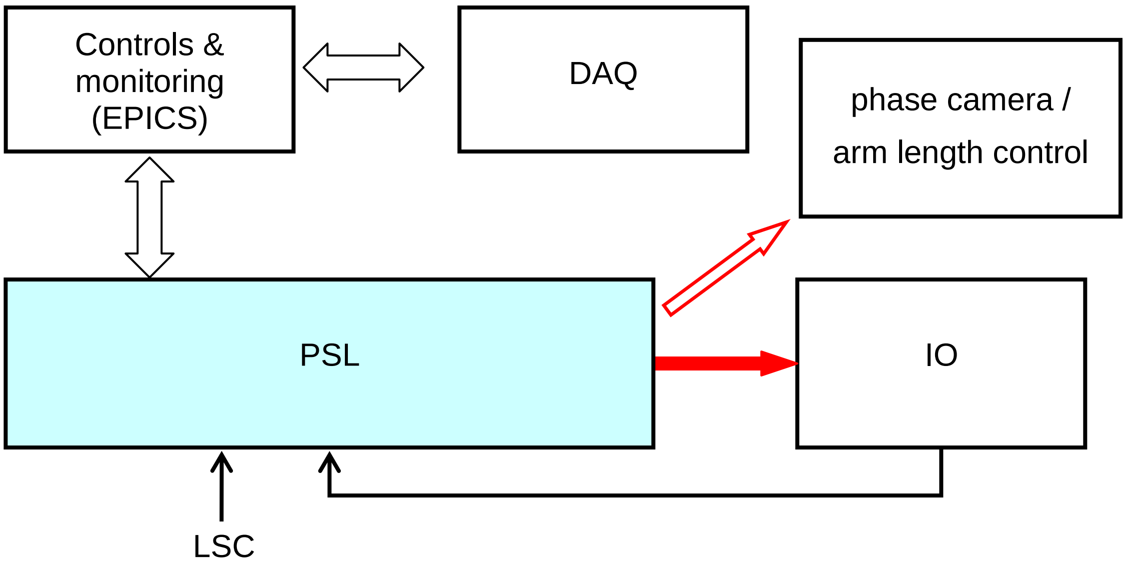

Figure 1. PSL subsystem, showing its relation to the interferometer.

1.3 Constraints, Assumptions and Dependencies

aLIGO must operate continuously, therefore this subsystem must be designed with high reliability and low mean-time-to-repair. The PSL subsystem incorporates several feedback control loops that enable the frequency and power of the laser radiation to be stabilized to very low fluctuation levels. Those control loops must acquire lock quickly and reliably via an automated sequence and maintain lock for long periods of time.

As far as they may influence the PSL design, the vibration and acoustic levels in the Laser and Vacuum Equipment Areas (LVEA) at the LIGO observatories should be taken to be those detailed in T010074 (rev. 3 at the time of writing), *"The LIGO Observatory Environment."*

The temperature and pressure in the LVEA are assumed to meet the design conditions given in the Civil Construction Facilities Design Configuration Control Document, Final Issue, July 3, 1996, LIGO-C960703-0, which specifies a design temperature of $72^\circ \pm 3.5^\circ$ F and pressure of 0.15 in. Hg above ambient.

1.4 Applicable Documents

Advanced LIGO Systems Design Document LIGO-T010075-v2

Interferometer Sensing and Control (ISC) Design Requirements LIGO-T070236-00,

Advanced LIGO Input Optics Design Requirement Document LIGO-T020020-v2

Advanced LIGO Input Optics Final Design Document LIGO-T0900386-v2

2 Requirements

2.1 Beam characteristics

Property	Value	Comment
Wavelength	1064 nm	Same as initial LIGO
Fundamental Mode Power	≥ 165 W	At the IO interface, in a circular TEM_{00} mode
Higher-order Mode Power	≤ 5 W	
Polarization	horizontal, > 100:1 ratio	At IO interface, parallel to table surface, to ±1 deg
Beam size	550 μm	Beam waist at IO interface
Beam height	4 inches	At IO interface, from table surface
Alignment tolerance	± 2 deg	with respect to the vertical plane defined by the table surface

Table 1. Specifications for the PSL beam, as delivered to the IO subsystem.

2.2 Laser power stability & noise

Long term stability. The laser power can be stabilized on time scales longer than ~10 sec through the interferometer control and monitoring systems (EPICS), using any (or a combination of) the various interferometer power monitors. The PSL is required to provide an appropriate control input to enable such stabilization with up to 1% peak-to-peak variations at the PSL/IO interface, over time scales up to 24 hours. The PSL power should also be reasonably stable on its own, exhibiting peak-to-peak power fluctuations less than 5% over any 24 hour period. The PSL should be designed in a way to deliver its nominal output power for at least one year without scheduled service interventions.

Control band fluctuations. The control band is defined as the range 0.1-10 Hz. Good power stability is required in this band to control the fluctuating radiation pressure forces on the suspended optics. The goal is that the radiation pressure-induced optic motion be smaller than the seismically induced motion which translates into the requirement shown in Fig. 2. The blue curve is the result of taking the BSC ISI motion (requirement curve), filtering it by the quad suspension transfer function and then computing the laser power noise that would cause a test mass motion equal to the filtered ISI noise, expressed as relative power noise (RIN) at full power operation (calculation done by Matt Evans, Dec 2009). Above 4 Hz a common mode effect is expected for the RIN induced motion. An assumed common mode rejection factor of 200 at 10 Hz leads to a smooth connection to the GW band requirement of $2\times10^{-9}\ \mathrm{Hz}^{1/2}$.

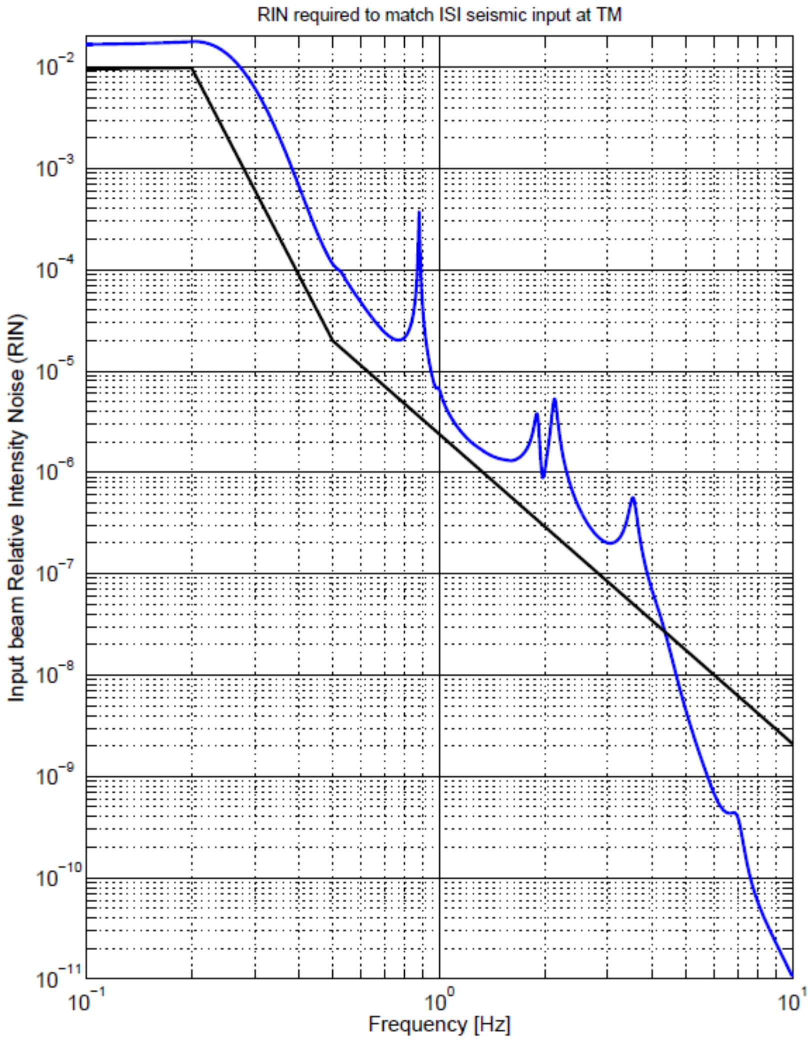

Figure 2 Relative power noise requirement in the control band. The blue curve shows the RPN level that would via radiation pressure produce a test mass motion equivalent to the expected seismically excited motion. The black curve indicates the PSL requirement.

GW band noise. The PSL power noise requirement at the input to the interferometer, in the GW band, is shown in **Figure 3** (The requirement was revised during the FDR see see LIGO-L-1000084-v2 and LIGO-L1000084-v2 and aLIGO sytems WIKI, length-sensing and control subsystem section, http://ilog.ligo-wa.caltech.edu:7285/advligo/RIN_requirements_at_low_power). At frequencies below a few hundred Hertz, the dominant coupling mechanism is technical radiation pressure imbalance in the arm cavities, creating a net differential displacement of the test masses. The PSL power noise requirement assumes an arm cavity average arm power imbalance of 1%. The radiation pressure effect is heavily low-pass filtered optically and mechanically, and at higher frequencies the dominant coupling is directly through the interferometer's anti-symmetric (AS) port sensing (the DC offset imposed on the differential arm length to produce the homodyne readout).

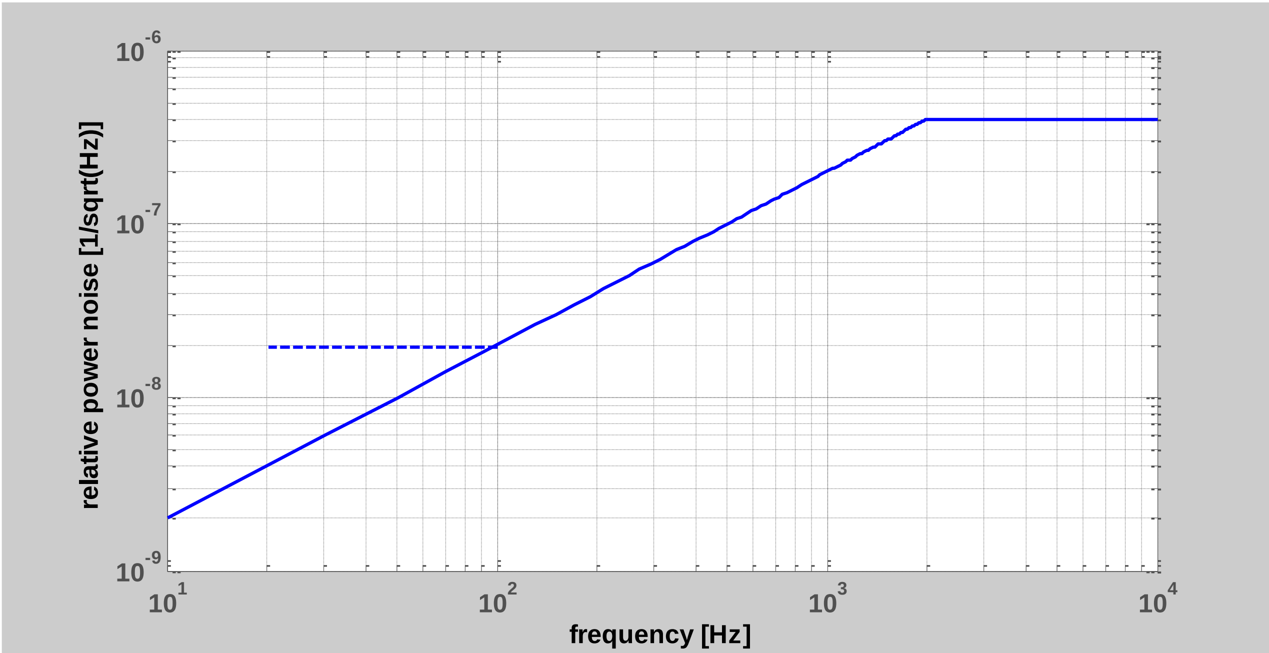

Figure 3. Relative power noise requirement for the light incident on the power recycling mirror. This requirement was revised during the final design review (see LIGO-G-1000106-v1 and LIGO-L1000084-v2). The dashed curve indicates the relaxed requirement for the inner loop.

Amplitude noise at the power line frequency and its harmonics. Care has to be taken in the PSL design to reduce the amplitude at the power line and its harmonics to a level no greater than 30 dB above the broadband noise (1Hz bandwidth) in the surrounding frequency range.

Amplitude noise between 10kHz and 9MHz

The laser amplitude noise must be below $2 \times 10^{-7}\,\mathrm{Hz}^{1/2}$ for frequencies between 10kHz and 9MHz. Narrowband signals above this level may be acceptable depending on their exact frequencies.

Amplitude noise in the RF band. The laser amplitude must be close to shot-noise limited at the RF modulation/demodulation frequencies, to maintain low sensing noise in the interferometer auxiliary degrees-of-freedom. *Requirement: for frequencies f > 9 MHz, the broadband PSL amplitude noise must be less than 1 dB above the shot-noise in an average photocurrent of 100 mA.* Narrowband signals above this level may be acceptable depending on their exact frequencies.

2.3 Frequency stability & noise

Long term stability. The long term frequency stability should be such that the fractional frequency variations are much smaller than the fractional arm length variations. The latter are principally due to tidal stretching (for time scales longer than of order one minute), with arm length changes up to a few hundred microns. The frequency stability requirement is set to be equivalent to 1 micron of arm length *change. Specifically, for time scales longer than 100sec, the laser frequency must be stable to within 1MHz (or no less stable than the InL PSL, whichever is more stringent, TBM).*

Control band fluctuations. In the control band (0.1 – 10 Hz), the PSL frequency serves as the reference for interferometer lock acquisition. Therefore, the control band fractional frequency fluctuations must be much smaller than the fractional arm length fluctuations due to seismically driven, locally damped test masses, as follows:

Frequency band	*Frequency stability req.*	*Compared to TM motion*
1 – 10 Hz	< 3 Hz-rms	5x lower
0.4 – 1 Hz	< 100 Hz-rms	10x lower
0.1 – 0.4 Hz	< 1000 Hz-rms	10x lower

Table 2. Requirements on the PSL frequency fluctuations in the control band.

GW band frequency noise. The PSL frequency noise requirement in the GW band is shown in Figure 4.

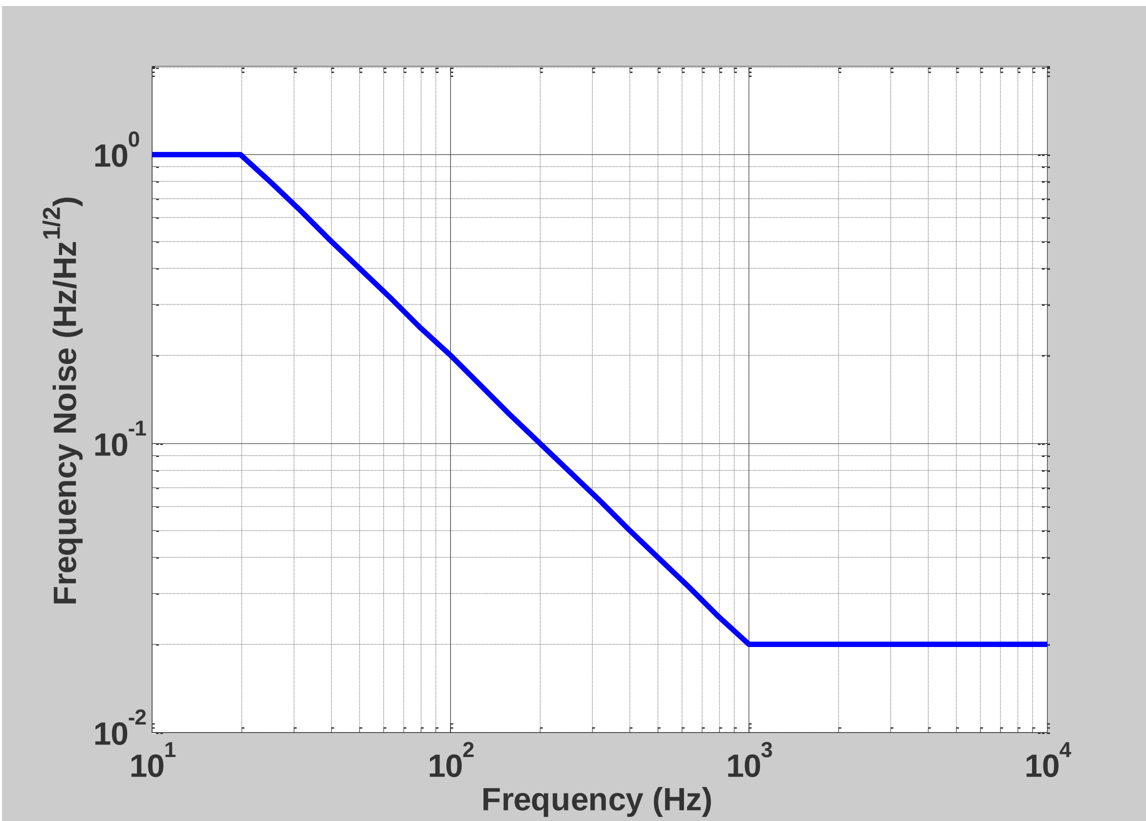

Figure 4. PSL frequency noise requirement in the GW band.

Frequency noise at the power line frequency and its harmonics

Care has to be taken in the PSL design to reduce the frequency fluctuations at the power line and its harmonics to a level no greater than 30db above the broadband noise (1Hz bandwidth) in the surrounding frequency range..

2.4 Beam pointing stability

The directional stability of the PSL beam, at the IO interface, must be reasonably good, though it is the responsibility of the IO subsystem to deliver the final interferometer input beam pointing stability. The requirement for the pointing stability of the beam at the PSL / IO interface is (see LIGO-T0900142-v2):

$\varepsilon_1 < 2.5\times10^{-6}\sqrt{1+\left(\frac{100\,\mathrm{Hz}}{f}\right)^4}\ \mathrm{Hz}^{-1/2}$, with $\varepsilon_1 = [(\delta\tilde{\alpha}(f)/\theta_D)^2 + (\delta\tilde{x}(f)/\omega_0)^2]^{1/2}$, where $\delta\alpha$ and $\theta_D = \lambda / (\pi\times\omega_0)$ being the angle fluctuations and divergence angle of the beam, respectively, and with δx and ω_0 being the translational fluctuations and waist size of the beam, respectively.

The above requirement applies to both horizontal and vertical directions.

2.5 Frequency control

The PSL must supply two frequency modulation inputs, one being a 'wideband input' for fast frequency control, the other being the former 'tidal input'. The requirements for these inputs are the same as for initial LIGO, with some reduction in the required wideband input range. Given the large range of the SEI subsystem's hydraulic actuators, the tidal effects will most likely be compensated for by a simple correction of the arm lengths at all frequencies (rather than having the laser frequency follow the arms at tidal frequencies). As a slow frequency control input might be useful for other purposes, the tidal input should be kept operational. The requirements for the two inputs are given in Table 3.

Wideband frequency input		
	Bandwidth	less than 20 degrees phase lag at 100 kHz (can be relaxed to 20 degree at 50kHz ((see LIGO-L1000084-v2))
	Range:	DC-1 Hz: 1 MHz pk-pk
		f > 1 Hz: 10 kHz pk-pk
Tidal frequency input		Range: 50 MHz pk-pk
		Speed: time constant < 5 h

Table 3. Requirements for the PSL frequency control inputs

2.6 Power control

Coarse control of the laser power sent into the interferometer is the responsibility of the Input Optics (IO) subsystem, and the PSL should nominally deliver its full power to the IO interface. However, the PSL is required to provide a small-signal amplitude modulation input, for global diagnostics use. *The modulation input must have a bandwidth of DC-10 kHz (or greater), with a minimum range of ±0.4% power modulation over this bandwidth.*

2.7 Diagnostics

A diagnostic capability must be included in the PSL design to allow determination of the subsystem's performance. This may be done through a combination of internal PSL diagnostics and interfacing to the Global Diagnostics Subsystem. Some examples of diagnostics that must be supplied:

- Monitoring of laser power levels at key points in the subsystem
- Monitoring of the loop gains of the frequency pre-stabilization, the amplitude stabilization and the PMC servos
- Out-of-loop monitor of the GW band amplitude noise
- Monitoring of the health of the high power laser; e.g., temperature monitors, pump diode I-V and light output monitors, etc.

2.8 Reduced power mode

For commissioning and possible low frequency optimized interferometer operation the PSL should be able to operate stable and reliable with a reduced output power of about 10W. In this operation mode full control and diagnostics capability has to be maintained. All stabilization control loops should be able to operate at the reduced power, at least with slightly reduced performance level.(For the power noise requirement in low power mode see http://ilog.ligo-wa.caltech.edu:7285/advligo/RIN_requirements_at_low_power).

It is not required to switch between the high and low power mode remotely. A duration of approximately one day to switch between the two modes with alignment and tuning work in the laser room is acceptable.