LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Advanced LIGO Photon Calibrator Design Requirements Document

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1 Introduction and General Description

1.1 Purpose

The purpose of this document is to describe the design requirements for the Auxiliary Optics System (AOS) Photon Calibrator.

1.2 Photon Calibrator Scope

The Photon Calibrator subsystem will provide a light beam that actuates the End Test Masses (ETMs) of the interferometer by means of radiation pressure. It will take its control signals from the DAQS system, and its internal signals will be monitored by DAQS. All software and electronics necessary to control the Photon Calibrator subsystem to faithfully respond to the control signals provided by the DAQS system are part of the scope. The Photon Calibrator does not send or receive any control signals from the SUS subsystem. No optic in LIGO other than the ETMs will have Photon Calibrators.

1.3 Photon Calibrator Perspective

Radiation pressure provides a potentially very well-characterized force on a mirror that can be used to calibrate the interferometer response to gravitational waves. This calibration is complementary to other techniques, such as calibration through error signal analysis of optics swinging through fringes. The Photon Calibrator provides this force and the means to sufficiently characterize it.

1.4 Photon Calibrator and Photon Calibrator Controls Functions

The Photon Calibrator shall reflect off a surface of the ETM a laser beam whose power is controlled by signals provided by DAQS. This power will itself be measured and stored for data analysis.

The main purpose of the Photon Calibrator is to provide actuation on the ETM for calibration purposes.

1.5 Photon Calibrator and Photon Calibrator Controls Constraints

LIGO must operate continuously; therefore this subsystem must be designed with high reliability and low mean time to repair. As this subsystem introduces light into the interferometer vacuum chamber, it must not introduce significant stray light at the interferometer sensing ports, especially the GW channel.

1.6 Assumptions and Dependencies

1.6.1 Core Optics Parameters

The following ETM parameters were taken from RODA: Core Optics sizes, including TMs, BS, FM and RM: LIGO-M050397-02-Y.

Physical Quantity	ETM
Mirror diameter, mm	340
Mirror thickness, mm	200

Table 1: ETM size parameters.

The following ETM parameters were taken from Core Optics Components Design Requirements Document: LIGO-T000127-01-D.

Physical Quantity	ETM
AR coating @ 1060 nm	<0.0002
mirror reflectivity @ 1060 nm	0.999965
beam radius parameter w, mm[1]	60

Table 2: ETM coating and beam spot size parameters.

1.6.2 Displacement Noise Parameters

Since the Photon Calibrator actuates the ETM, it is natural to define its force noise requirements analogously to those for SUS actuators. The force noise requirements in this document are referenced to the longitudinal displacement noise requirement for the test masses. As specified in the Cavity Optics Suspension Subsystem Design Requirements Document LIGO-T010007-03, this requirement is $5\text{x}10^{-20}$ m/$\sqrt{\text{Hz}}$ at 10 Hz, falling as 1/f for test mass internal thermal noise motion, and 10^{-19} m/$\sqrt{\text{Hz}}$ at 10 Hz, falling as $(1/f)^2$ for suspension thermal noise motion.

[1] Derived for specificied mirror g-factor of -.9265 and arm cavity length of 4 km.

2 Requirements

2.1 Photon Calibrator Performance Characteristics

2.1.1 Calibration Line Strength

The Photon Calibrator shall provide sufficient force to the ETM to produce a calibration line with an SNR>10 over the expected Advanced LIGO sensitivity curve with an integration time of 1 s for frequencies up to 500 Hz.

It is useful to re-express the requirement above in terms of delivered power, since this can be measured directly at the output of the Photon Calibrator. The SNR is given by

$$SNR = \sqrt{\frac{2E}{N}}$$

where N is the single-sided noise power spectral density, and

$$E = \int_0^T dt\left[s_0 \cos(2\pi f)\right]^2$$

is the signal strength. Taking $N = \left(2.4 \times 10^{-20}\, m/\sqrt{Hz}\right)^2$ at 500 Hz[2], the SNR is then

$$SNR = \frac{s_0\sqrt{T}}{2.4\times 10^{-20}\, m/\sqrt{Hz}}.$$

Thus $s_0 > 2.4 \times 10^{-19}\, m$. The power required at normal incidence and with 100% reflection to produce this displacement at 500 Hz is

$$P = \frac{cms_0(2\pi \times 500Hz)^2}{2} = 14.2mW.$$

The applied force is 94.7 pN.

2.1.2 Calibration Line Accuracy

The displacement of the HR surface of the ETM caused by the Photon Calibrator shall be absolutely known to within 5%.

2.1.3 Intensity Noise

In order that the Photon Calibrator induce less than 1/10th the displacement noise required for the ETM if it is used during data collection, the noise force shall be less than the upper limit of $7.9\text{x}10^{-16}$ N/√Hz at 10 Hz, rising as f, and $1.6\text{x}10^{-15}$ N/√Hz, independent of frequency.

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[2] From Figure 1 of Advanced LIGO Systems Design Document: LIGO-T010075-00-D.

Occasional large glitches in the power output of the Photon Calibrator can be interpreted as gravitational wave bursts. If large enough, they could potentially throw the interferometer out of lock. Glitches in the Photon Calibrator power output large enough to induce detectable glitches in the GW channel at design sensitivity shall be detected within the Photon Calibrator subsystem. The rate of such 'GW-detectable' glitches shall be less than one per week. The size of a lock-ending glitch is not known as of the writing of this document.

2.1.4 Force Centering

The Photon Calibrator force centering on the ETM shall be sufficient that operation of the Photon Calibrator over its full power range does not tilt the ETM beyond the technical pitch and yaw noise requirements specified in the Cavity Optics Suspension Subsystem DRD. In addition the Photon Calibrator beam jitter shall be sufficiently small that at full power it does not tilt the ETM beyond the technical pitch and yaw noise requirements specified in the Cavity Optics Suspension Subsystem DRD. In addition, the Photon Calibrator centering shall be sufficient to satisfy the displacement certainty mentioned above.

2.2 Photon Calibrator Interface Requirements

2.2.1 Mechanical Interfaces

Any steering and/or folding mirrors inside the vacuum shall bolt to the SEI BSC platform. Lasers and optics external to the vacuum system shall reside on optical benches supported from the floor by piers and contained within optical enclosures.

2.2.2 Electrical Interfaces

The Photon Calibrator shall receive a digital control signal from DAQS proportional to the force required (equivalently, the output light power).

2.2.3 Optical Interfaces

The Photon Calibrator beams will pass through viewports provided in the spools nearest the ETM BSC chambers and reflect off of one or more spots on the HR surfaces of the ETMs. The reflected beams will be collected by beam dumps within the vacuum.

2.2.4 Stay Clear Zones

Any steering or folding mirrors or beam dumps inside the vacuum tank must stay clear of the 1ppm radius of the main arm cavity beam. They must also not interfere with other auxiliary optic beams or apertures, such as sampled ETM transmission beams, cameras, or optical lever beams.

2.3 Generic Requirements

The Photon Calibrator shall be subject to the generic requirements enumerated in LIGO Document LIGO-E010613-01-D, "Generic Requirements & Standards for Detector Subsystems," and those LIGO documents specified therein. The subsections below elaborate upon these generic requirements for the specific case of the Photon Calibrator.

2.3.1 Photon Calibrator Reliability

The laser used in the Photon Calibrator could operate continuously for months. It is also expected to be a relatively conservative technology. It therefore must operate with a Mean Time Between Failures (MTBF) of one year for out of vacuum components and three years for in-vacuum components, which require a vacuum vent to service.

Recalibration of the Photon Calibrator shall require no more than one day to perform.

2.3.2 Photon Calibrator Maintainability

The Photon Calibrator is not a critical subsystem, and therefore the laser and optics external to the vacuum system will require no more than one month to replace or repair.

2.3.3 Optical Safety

The Photon Calibrator and Photon Calibrator Controls subsystem shall conform to safety requirements described in documents LIGO-M040112-07, “LIGO Livingston Observatory Laser Safety Plan,” and LIGO-M020131-01, “LIGO Hanford Observatory Laser Safety Plan.”

2.3.4 Seismic Environment

The Photon Calibrator must be able to operate through the 95th percentile limits of ground motion as specified in LIGO-E010613-01-D. In particular, when estimating calibration error or injected noise due to seismically induced Photon Calibrator beam jitter the Photon Calibrator and its mounting pier are assumed to be subject to the above specified ground motion.

2.3.5 Photon Calibrator Interchangeability

The Photon Calibrators and Photon Calibrator Controls for all interferometers shall be identical in design except for the steering mirrors leading into and out of vacuum and the in-vacuum optics, which may be specially designed to adapt to differences in positioning of the ETMs in the different interferometers. Mirror symmetry of optical layout is considered to be ‘identical’ in this context. Specific components which shall be interchangeable between specific instances of the Photon Calibrator include: the laser, the power modulator, all photodetectors, all extra-vacuum optics and all electronic control modules.

2.3.6 Photon Calibrator Logistics

There will be two Photon Calibrators operating on each interferometer. Within one interferometer, each Photon Calibrator shall be the operational spare for the other.

A NIST-traceable absolute radiometer is required to perform the absolute calibration of the Photon Calibrator output optical power.

2.3.7 Photon Calibrator Precedence

The highest priority of the Photon Calibrator is to provide the required power range and bandwidth, with the power noise and absolute calibration within requirements. Long-term reliability and size and rate of rare power glitches are of secondary priority.

2.3.8 Responsibility for Tests

Responsibility for all testing shall be with AOS. Reliability of the Photon Calibrator laser will be determined by tests on a prototype unit used in the Preliminary Design Phase.

2.3.9 Acronyms

AOS – Auxiliary Optics System

ETM – End Test Mass

DAQS – Data Acquisition System

SUS – Suspension Subsystem

GW – Gravitational Wave

SNR – Signal to Noise Ratio

DRD – Design Requirements Document

SEI – Seismic Isolation

BSC – BeamSplitter Chamber

MTBF – Mean Time Between Failures

AR - Antireflection Coating

HR - Reflective mirror coating

3 Applicable Documents

Advanced LIGO Systems Design Document, LIGO-T010075-00-D.

Generic Requirements & Standards for Detector Subsystems, LIGO-E010613-01-D.

RODA: Core Optics sizes, including TMs, BS, FM and RM: LIGO-M050397-02-Y.

Core Optics Components Design Requirements Document, LIGO-T000127-01-D.

Cavity Optics Suspension Subsystem Design Requirements Document, LIGO-T010007-03-D.