LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Large Optics Suspension Final Design (Mechanical System)

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1 INTRODUCTION

1.1. Purpose and Scope

This Final Design Document (FDD) provides a final design of the mechanical system of Large Optics Suspension (LOS) and demonstrates by analysis and experiment that the final design meets the Suspension System (SUS) design requirements.

1.2. Acronyms

- LOS: Large Optics Suspension

Acronyms for names of subsystems should be referred to [5] “LIGO DETECTOR Construction Phase Implementation Plan”, LIGO-1401051 Rev. B (p. 13).

1.3. Applicable Documents

1.3.1. LIGO Documents

[1] “Core Optics Components Requirements (1064 nm)”, LIGO-E950099-01-D
[2] “Dumbbell-type Standoff for Magnet/Standoff Assembly”, LIGO-T970096-00-D
[3] “Estimate of the Effect of Scattered Light on the Suspension Sensor”, LIGO-T960076-00-D
[4] “Investigation of Violin Mode Q for Wires of Various Materials”, LIGO-P960037-26-D
[5] “LIGO DETECTOR Construction Phase Implementation Plan”, LIGO-1401051 Rev. B
[6] “Loss due to Eddy Current Damping between Magnets and Sensor/Actuator Head Holders in the Small Optics Suspension”, LIGO-T970073-01-D
[7] “Pendulum Thermal Noise: Pendulum and Pitch Mode”, LIGO-T960081-00-D
[8] “Response of Pendulum to Motion of Suspension Point”, LIGO-T960040-00-D
[9] “RGA Scanning Test of Sensor/Actuator Head and Kapton Cable”, LIGO-T970094-02-R
[10] “Large Optics Suspension Assembly Specification”, LIGO-E970038-00-D
[11] “Suspension Design Requirements”, LIGO-T950011-19-D
[12] “Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detector”, LIGO-P940011-00-R
[13] “Thermal Noise in the Initial LIGO Interferometer”, LIGO-P950006-00-I
[14] “Thermal Noise in the Test Mass Suspensions of a Laser Interferometer Gravitational-Wave Detector Prototype”, LIGO-P930001-00-R

1.3.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Design Requirements

The final design of LOS must meet the SUS requirements for LOS described in [11] “Suspension Design Requirements”, LIGO-T950011-19-D.

2.2. Design Philosophy

The following design philosophy are considered for the final design:

- Reliability
- Simplicity
- Tractability
- Safety
- Minimal excess noise

2.3. Dependencies

The size for Large optical components for each suspension is listed in Table 1.

Table 1: Size and optical clear aperture of suspended components.

Physical Quantity	*LOS 1*					*LOS 2*		*LOS 3*
	a	*b*	*c*	*d*	*e*	*a*	*b*	
Optic name	ETM	ITM, 4k	RM, 4k	ITM, 2k	RM, 2k	BS, 4k	BS, 2k	FM
Diameter of Suspended Component (mm)	250					250		250
Thickness of Suspended Component (mm)	100[a]					40[b]		100[c]
Weight of Suspended Component (kg)	10.3	10.5	10.2	10.7	10.2	4.6	4.6	10.3
Optical Clear Aperture (mm)	ϕ194					ϕ217 45° incidence		ϕ194 45° incidence
Wedge Angle of Optic (°) (vertically configured)	2.000	1.167	2.406	.567	2.406	1.000	1.000	2.000
Orientation of thick side	up	up	down	up	down	up	up	up
Beam Height (mm)	-100	-100	26	-100	43	-57	-15	-100

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[a] The thickness is measured at the thickest part of the substrate.

[b] The thickness is measured at the thinnest part of the substrate.

[c] The thickness is measured at the thickest part of the substrate.

3 FINAL DESIGN

3.1. Design Overview

A final design of the mechanical system of LOS is schematically illustrated in Fig. 1. General features of the design are:

- A suspension assembly is held together by a **suspension support structure**.
- An optical component is suspended by a single loop of **suspension wire** from a **suspension block.**
- **Wire standoffs** and **guide rods** are used to balance the optical component roughly in pitch.
- The optical component is damped and actuated by six **magnet/standoff assemblies** which are glued to the optical component and five **sensor/actuator heads** which are mounted on **head holders**.
- Fine control of pitch is achieved with four **pitch adjustment magnets**.
- The optical component is protected during operation or held firmly during transfer by **safety stops**.
- The suspension support structure is strengthened by a **stiffener bar** to increase its resonance frequencies.

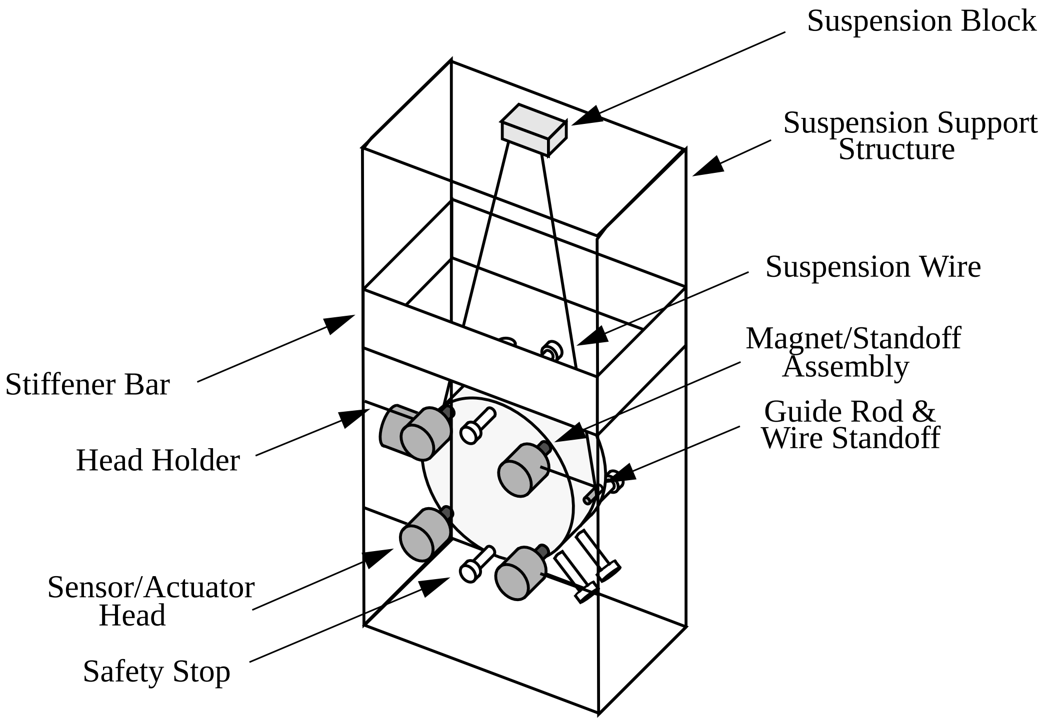

Fig. 1. Schematic view of the mechanical system of the LOS suspension.

3.2. Suspension Configuration

A single loop of wire suspends the optical component. A sketch of the configuration of a suspended component is given in Fig. 2. The important design parameters of this single loop suspension are:

- Length of the pendulum ($d_{pendulum}$ in Fig. 2)
- Vertical deviation of the center of mass from the center of cylinder due to wedge of the optical component (d_{CM})
- Distance between the two suspension points at the upper release points (d_{yaw})
- Height from a horizontal level through the center of cylinder to the wire release points (d_{pitch})
- Diameter of the wire standoff ($d_{standoff}$)
- Minimum distance between the wire and the optical component above the wire release points (d_{margin})

These parameters are chosen to satisfy the desired pendulum, pitch, and yaw frequency for a $d_{margin} \approx 1$ mm as shown in Table 2.

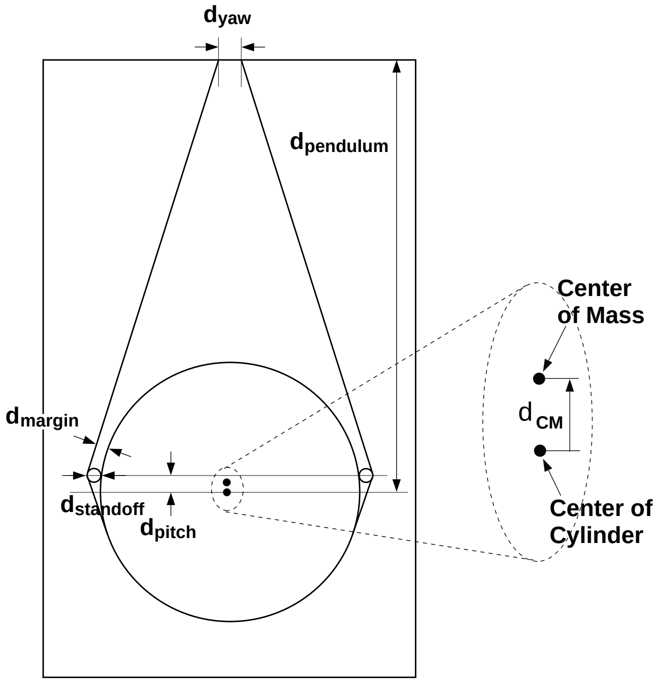

Figure 2: Sketch of the suspension configuration with the definition of parameters.

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Table 2: Parameters of the LOS suspension configuration.

Parameters	*LOS 1*					*LOS 2 a, b*	*LOS 3*
	a	*b*	*c*	*d*	*e*		
Optic name	ETM	ITM, 4k	RM, 4k	ITM, 2k	RM, 2k	BS, 4k,2k	FM
Pendulum Frequency (Hz)	.744	.743	.741	.743	.741	.744	.744
Pitch Frequency (Hz)	0.600	0.600	0.600	0.600	0.600	0.600	0.600
Yaw Frequency (Hz)	0.500	0.499	0.501	0.497	0.501	0.500	0.500
Violin Frequency (Hz)	336	339	334	341	334	223	336
Vertical Frequency	12.85	12.72	12.86	12.63	12.86	19.36	12.85
$d_{pendulum}$ (mm)	450	450	450	450	450	450	450
d_{CM} (mm)	1.4	0.8	-1.8	0.4	-1.8	1.6	1.4
d_{pitch} (mm)	8.2	7.63	4.92	7.24	4.92	7.5	8.2
d_{yaw} (mm)	33.3	33.3	33.3	33.3	33.3	28.9	33.3
$d_{standoff}$ (mm)	ϕ2.8	ϕ2.8	ϕ3.5	ϕ2.8	ϕ3.5	ϕ2.8	ϕ2.8
d_{margin} (mm)	0.956	0.824	0.824	0.734	0.824	0.681	0.956

3.3. Design Detail

3.3.1. Suspension Support Structure

The suspension support structure is a rectangular frame on which the head holders and the stiffener bars welded. This modular support structure makes it possible to assemble the system on a clean bench and then transfer it into the chamber without changing the relative position of the optical component to the sensor/actuator head.

- Material: 304 Stainless

3.3.2. Wire

Steel music wire was selected as the suspension fiber material because of its good Q value. (See [4] “Investigation of Violin Mode Q for Wires of Various Materials”, LIGO-P960037-26-D for detail.) The diameter of the wire is chosen so that the wire will be loaded to one-half its breakage stress, to obtain the lowest possible wire losses and the smallest number of violin modes in the gravitational-wave signal band, without incurring undue risks due to wire failure or the production of excess non-gaussian noise (through acoustic emission from the loaded wire).

A single loop wire is used to suspend the optical component.

- Type: Steel music wire
- Density: 7.8 g/cm^3
- Diameter: 0.31mm [.0122”]
- Ultimate Tensile Strength: 21.4 kg
- Young's modulus: $2.068 \times 10^{11} \mathrm{N/m}^2$
- Yield strength: 75% of breaking strength

3.3.3. Suspension Block

The suspension wire is hung down from the suspension block which is a part of the suspension support structure. The suspension block has two guide pins and a clamp so that the distance of the wire at the bottom of the suspension block (d_{yaw}) may be maintained properly (Fig. 3). The two wire clamps above the guide pins may be used to clamp the wire while the wire length is adjusted.

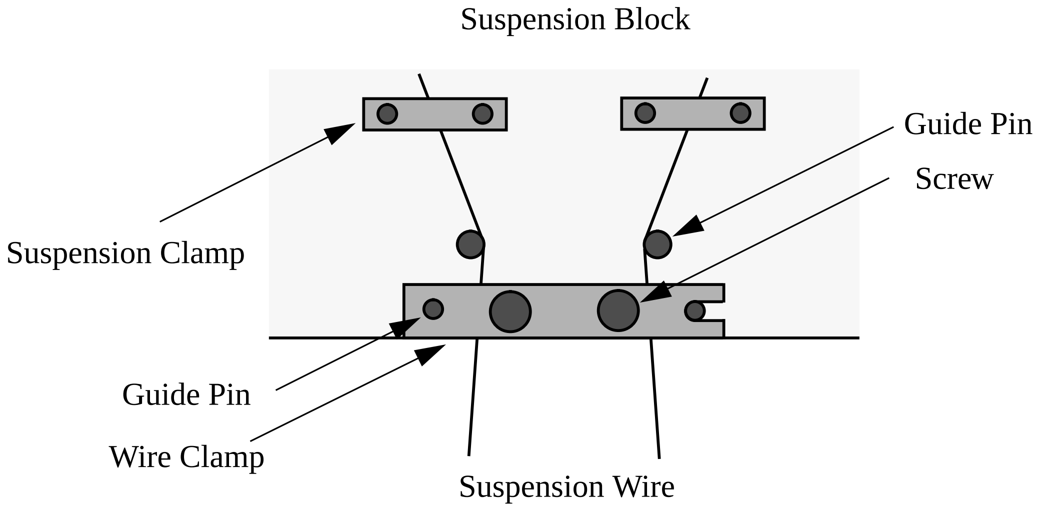

Fig. 3. Suspension block.

3.3.4. Wire Standoff and Guide Rod

A wire standoff is glued to one side of the optical component, while a guide rod is glued to the other side. Another wire standoff is placed below the guide rod between the optical component and the wire. The optical component can be balanced in pitch by adjusting the position of the wire standoff along the guide rod (Fig. 4). The wire standoff has a groove on it so that the wire does not slip on the rod.

- Wire standoff
    - Material: Quartz

- Guide rod
  - Material: Aluminum
- Glue
  - Vacseal
  - Care should be taken so that the glue is not put on the wire.

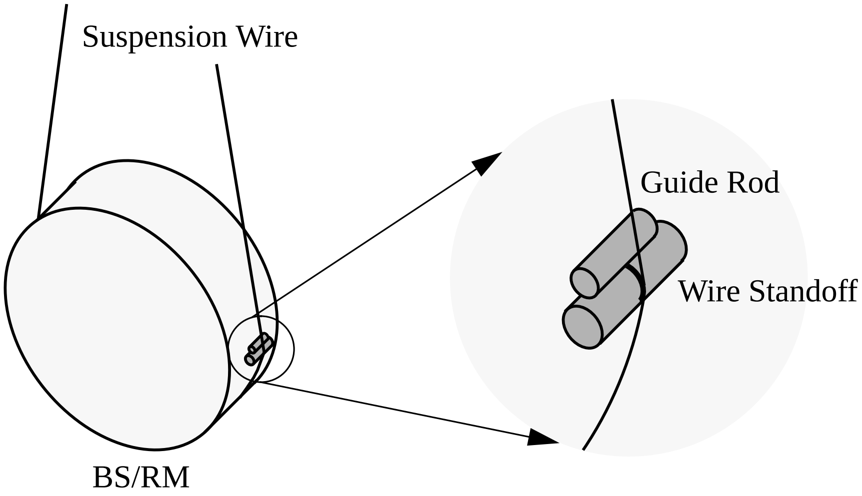

Fig. 4. Guide rod and wire standoff.

3.3.5. Magnet/Standoff Assembly

Aluminum standoffs are used as buffers between the magnets and the optical component to protect the internal mode *Q*s of the component from the lossy magnets. The standoff has a dumbbell type shape as shown in Fig. 5, which makes the assembly robust. See [2] “Dumbbell-type Standoff for Magnet/Standoff Assembly”, LIGO-T970096-00-D for detail.

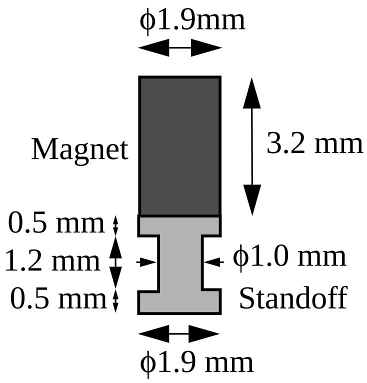

Fig. 5. Magnet standoff assembly.

Six magnet/standoff assemblies are attached to the optical component (Fig. 6): four on the front surface and two on the side surface of the optical component. The magnets are placed so that polarities of the magnets alternated; this is to prevent the optical component from being shaken in position and orientation, by time-varying ambient magnetic field.

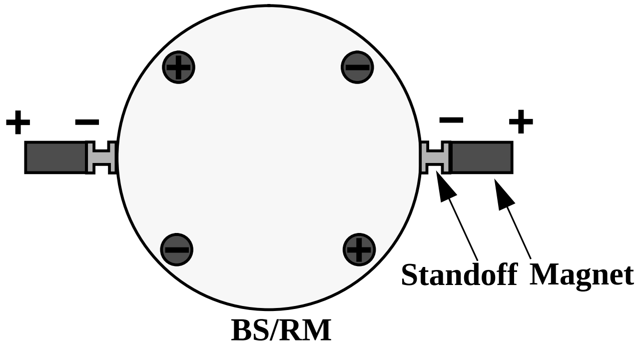

Fig. 6. Configuration of the magnet/standoff Assembly.

- Magnet
  - Material: Nd:Fe:B (NEO-35, Curie temperature 337 ˚C)
  - Size: See Fig. 5
- Standoff
  - Material: aluminum
  - Size: See Fig. 5
- Glue
  - Vacseal
- Resonances when attached to the optical component
  - Frequency: 9.7 kHz
  - Q: 130

3.3.6. Sensor/Actuator Head

The sensor/actuator head consists of a pair of an LED and a photodiode, a coil, and a housing. Five sensor/actuator heads are supported by the head holders which are mounted or located on the suspension support structure: four sensor/actuator heads on back and one sensor/actuator head on one side.

The LED-photodiode system senses the shadow of the magnet, thus position of the optical component is detected. The current in the coil actuates the magnet attached to the optical component. The system is illustrated in Fig. 7.

The Macor housing is gold-coated to prevent the electrostatic charge-up problem.

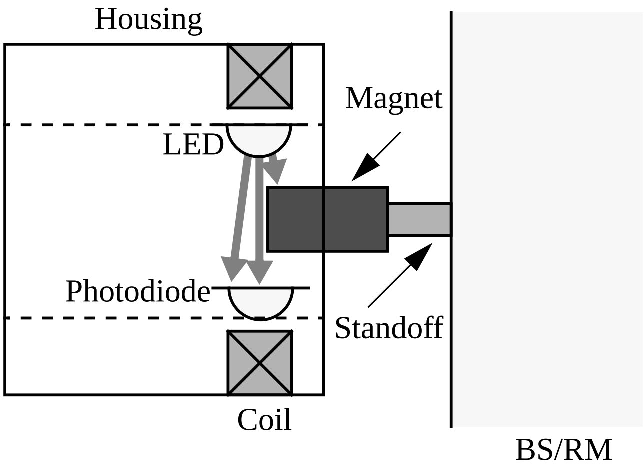

Fig. 7. Sensor/actuator head and the magnet/standoff assembly.

- LED: TLN107A, Toshiba, passed the RGA scanning test after being baked at 80°C
- PD: TPS703A, Toshiba, passed the RGA scanning test after being baked at 80°C (See [9] “RGA Scanning Test of Sensor/Actuator Head and Kapton Cable”, LIGO-T970094-02-R for detail.)
  - Distance between PD and LED: 6 mm
- Coil
  - Wire size: 0.22 mmD
  - Coil size: 7.66 mmID, 12.66 mmOD, 5 mmL
- Housing
  - Material: Macor (Machinable glass ceramic: manufactured by Corning)
  - Size: 25.3 mmOD × 48.3 mmL
  - Coated by Gold

3.3.7. Pitch Adjustment Magnets

There are four pitch adjustment magnets, of the same type mounted on the optic. Each is mounted on the end of a 32 threads per inch screw threaded into a bracket on the head holder. The screw passes up the hollow center of one of the sensor/actuator heads so as to bring the pitch adjustment magnet into opposition with the corresponding magnet mounted on the optic. The initial gap distance is 10 mm. Whereas the magnets on the optic have alternating polarities, the pitch adjustment magnets all face the same way. Thus among the four pairs of opposing pole faces there are two pairs of like poles and two pairs of unlike poles. When the ends of the pitch adjustment magnets are adjusted to lie in a plane parallel to the surface of the optic (the neutral condition), there is both zero net force and zero net torque. By adjusting the upper and lower magnets by equal amounts in opposite directions the pitch can be adjusted.

3.3.8. Head Holder

The front head holders are welded on the suspension support structure. The head holder has a hole with machined line contacts and a set screw for the sensor/actuator head, so that the sensor/actuator head can be placed and fixed properly, without changing its transverse position. The head holder is made of stainless steel because of its relatively high resistivity and is located far enough from the magnets to reduce the eddy current thermal noise. See [6] “Loss due to Eddy Current Damping between Magnets and Sensor/Actuator Head Holders in the Small Optics Suspension”, LIGO-T970073-01-D.

- Material: Stainless steel
- Minimum distance between the head holder and the magnet: 15.7 mm (0.62”)

3.3.9. Safety Cage and Safety Stop

The motion of the optical component is restrained within 1 mm by a safety stop mounted on a suspension support structure to protect the optical component from large motion. The safety cage is also used to hold the suspended component during installation after it is assembled and balanced on a clean table. The safety stop is made of graphite filled teflon to prevent the electrostatic charge-up problem.

- Material: Graphite filled teflon
- 3/8-16 x 1.5 safety stops
- 1/2-13 x 3.0 chamfer stops

3.3.10. Cable and Cable Harness

The Kapton cables from the sensor/actuator heads are connected to the cable harness which is placed on the stack top plate.

3.3.11. Glue

Vacseal is used for gluing.

3.4. Fixtures

See [10] “Large Optics Suspension Assembly Specification”, LIGO-E970038-00-D

3.5. Installation

See [10] “Large Optics Suspension Assembly Specification”, LIGO-E970038-00-D.

4 DESIGN MATCH TO REQUIREMENTS

In this section it will be demonstrated by analysis, experiment, and common sense that the described design will meet the LOS design requirements for mechanical part.

4.1. Initial Pitch Imbalance

Initial pitch balancing can be done manually to a precision of better than 3 mrad. The pitch adjustment magnets exert sufficient torque to alter the pitch through a range of 3 mrad, using around ten turns on each of the four adjustment screw. Even if we assume pessimistically that the screw position is variable in increments of not less than a quarter of a turn, the initial pitch imbalance should be settable to 0.07 mrad. Experimental confirmation is expected before the FDR.

4.2. Transfer Function of LOS Suspension

4.2.1. Transfer Function from Horizontal to Horizontal, T_{hh}

It is self-evident that the requirement is met, considering the designed pendulum frequency.

4.2.2. Transfer Function from Horizontal to Pitch, T_{hp}

We analyzed it and concluded that the requirement will be met. See [8] “Response of Pendulum to Motion of Suspension Point”, LIGO-T960040-00-D.

4.2.3. Transfer Function from Vertical to Vertical, T_{vv}

It is self-evident that the requirement is met, considering the designed vertical frequency.

4.2.4. Transfer Function from Vertical to Horizontal, T_{vh}

It is probably OK, but it cannot be proven until it is measured.

4.2.5. Transfer Function from Vertical to Pitch, T_{vp}

We analyzed it and concluded that the requirement will be met. See [8] “Response of Pendulum to Motion of Suspension Point”, LIGO-T960040-00-D.

4.3. Resonance of Suspension Support Structure

The lowest resonance frequency of the LOS suspension support structure was measured to be 107 Hz.

4.4. Thermal Loss

Resonance frequencies and *Q*s of the pathfinder mass with the dumbbell-type standoffs, magnets, and wire standoffs were measured (See Table 3.)

Table 3: Resonance frequency and Q of the test mass internal mode.

Mode	*Resonance Frequency*	*Q*
Internal Mode	9.4764 kHz	1.3×10^6
	22.4215 kHz	4.6×10^5
	25.6323 kHz	2.6×10^6
	29.4842 kHz	1.1×10^6
	29.8662 kHz	Immeasurable
	38.7632 kHz	8.8×10^5
	42.7583 kHz	4.8×10^6
	47.3324 kHz	5.4×10^6
Magnet/Standoff Assembly	7.484 kHz	540

4.4.1. Internal Mode Thermal Loss

Internal mode thermal loss for the Large optical component was measured to be 8.2×10^{-7} in average for the first 8 resonances (one mode immeasurable). This meets the requirements.

4.4.2. Pendulum Thermal Loss

Violin mode thermal loss for the LOS suspension was extrapolated to be 5×10^{-6} (See [4] “Investigation of Violin Mode Q for Wires of Various Materials”, LIGO-P960037-26-D). The pendulum loss is one half of the violin mode loss. Therefore the pendulum loss is expected to be 3×10^{-6}. This meets the requirements.

4.4.3. Pitch and Yaw Thermal Loss

According to [7] “Pendulum Thermal Noise: Pendulum and Pitch Mode”, LIGO-T960081-00-D, the pitch mode loss would be worse than the pendulum mode loss by a factor of 33 that is the ratio of $d_{pendulum}$ to $2(d_{pitch} - d_{CM})$ (See Fig. 2 and Table 2). That leads to an estimated pitch mode loss of 8×10^{-5}. The yaw mode loss is considered to be much smaller than the pitch mode loss. They meet the requirements.

4.4.4. Vertical Thermal Loss

The estimated loss for LOS is 2.5×10^{-4}. This meets the requirements.

4.4.5. Eddy Current Damping Loss

The LOS eddy current damping loss was estimated from the measurement ([6] “Loss due to Eddy Current Damping between Magnets and Sensor/Actuator Head Holders in the Small Optics Suspension”, LIGO-T970073-01-D) to be at most $4.2\times10^{-7}\times\left(\frac{f}{100\mathrm{Hz}}\right)$. This meets the requirements.

The eddy current damping loss between the pitch adjustment magnets and the wire loop was estimated by Mark Barton and is utterly negligible (around 14 orders of magnitude in hand). The loss between the magnets on the optic and the gold plating on the Macor was similarly estimated and is negligible (3 orders of magnitude in hand) given the measured conductivity of the gold plating (2.7 Ω per square). Since the damping is proportional to the square of the conductivity, and since there may be a half order of magnitude uncertainty due to approximations in the calculation, for safety the gold plating should not be more than one order of magnitude more conductive than this.

4.5. Magnet Strength

Dennis Coyne analyzed this issue and concluded that the displacement noise caused by the fluctuation of the ambient magnetic field is negligible assuming that an imbalance of the magnets is 5%.