LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T010007-01 *ADVANCED LIGO* 16 Oct 2001

Cavity Optics Suspension Subsystem Design Requirements Document

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Distribution of this document:
LIGO Science Collaboration

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1 Introduction

1.1 Purpose and scope of this document

The Requirements and Interface Specifications for the Advanced LIGO cavity optics suspensions system are given. This document summarizes requirements that have flowed down from a systems design.

The scope of this document is limited to the specific requirements for the suspension subsystem (SUS) for the sensitive cavity optics: input and end test masses, power- and signal-recycling mirrors, beamsplitter, folding mirrors (in the BSC of the folded interferometer only), and the mode cleaner mirrors. It includes information necessary to quantify the relationship and define the interfacing to other subsystems, in particular the seismic isolation subsystem (SEI), core optics

(COC), auxiliary optics subsystem (AOS), and interferometer sensing and control (ISC). The general requirements for all types of suspensions are given in a companion document.

The requirements for all sensors and actuators, including electronics and actuator coatings on the test masses, are treated in this document, except for the photon drive actuator. In-vacuum wiring between the feedthrough and the connection block on the suspension system is not included in the assumed scope.

There are several types of suspensions for Advanced LIGO. Suspension designs for optics other than cavity optics will be detailed in other documents. The conceptual design is presented in a separate companion document.

1.2 Applicable Documents

- LSC White Paper baseline design description (LIGO-T990080-01-D).
- LIGO II Suspension Reference Design, The GEO Suspension Team, Jan 31 2000, (LIGO-T000012-00-D).
- LIGO II Suspension Conceptual Design Document (in progress).
- Universal Suspension Subsystem Design Requirements Document (LIGO-T000053-01-D).
- Auxiliary Suspended Optics Displacement Noise Requirements (LIGO-T010097-00-D).
- Advanced LIGO Systems Design (LIGO-T010075-00-D).
- Seismic Isolation Subsystem Design Requirements Document (LIGO-E990303-03-D).

2 General description

2.1 Functions of the Cavity Optics Suspensions

The suspension forms the interface between the core optics and the seismic isolation platform. It provides seismic isolation and the means to control the orientation and position of the optic. These functions are served while minimizing the compromise of the thermal noise performance of the optics and while contributing thermal noise from the suspension within requirements.

Local signals are generated and fed to actuators to damp solid body motions of the suspension components; in addition, control signals generated by the interferometer sensing/control (ISC) are received and turned into forces on the test mass to obtain and maintain the operational position and angular orientation.

The suspension system must:

- Support the test mass in a way which does not impair the functioning of the optical interferometer, either by occulting the light, causing stray reflections, or by responding to stray light.
- Optimize the thermal noise performance of the suspension and test mass given the material properties of those components
- Provide vibration isolation in conjunction with the isolation subsystem

- Provide a mechanical and functional interface with the isolation system
- Provide a mechanical and functional interface with the core optics system
- Provide sensors and actuation for local damping, suitable to maintain the total motion of the test mass or optics component within a level required for lock acquisition and normal operation. This must be considered in conjunction with the isolation and global control actuators. Control noise levels must lie below the target prescribed noise levels.
- Provide suitable actuation for global control, in conjunction with the isolation subsystem.

3 Requirements

3.1 Introduction

The practical procedure for determining the requirements for the suspension is as follows; some iteration is of course performed.

1. Parameterized models for the thermal noise performance of the suspension fibers and of the target test mass materials are made
2. Coarse mechanical (e.g., height) and electronic (e.g., damping system noise) limitations are determined
3. Best-guess parameters are inserted and a first cut at the range of performance and trades involved are generated
4. System trades are performed: The resulting performance curves are compared with other noise sources and with potential sources of signals, and the technical risk and cost are weighed
5. Requirements for the thermal noise performance and test mass material and size are established by the systems group and given to the suspensions group
6. The suspension subsystem group determines the mechanical and electrical design, and delivers the suspension isolation and actuator specification to systems where it is passed on to seismic isolation (i.e., the suspension design takes precedence in determining the isolation available).

The process is presently roughly at step 5 above. There are several top-level system trades to be performed which have great impact on the suspension design, and the choice of fibers or ribbons, and detailed requirements or anticipated specifications will have to await their resolution:

- Choice of test mass material and dimensions
- Choice of lower-frequency limit of observation band
- Optical noise in the range 10-50 Hz.

3.2 Characteristics

3.2.1 Performance Characteristics: Test Mass Suspensions

3.2.1.1 Assumptions and Dependencies

There are two variants of the test mass suspension: one for the ETM which carries potentially non-transmissive actuators behind the optic, and one for the ITM which must allow the input beam to couple into the Fabry-Perot arm cavity. The test mass suspension system is mounted (via bolts and/or clamps) to the BSC seismic isolation system by attachment beneath the BSC SEI optics table. In the folded interferometer the input test masses will share a platform with the folding mirror suspensions; the resulting weight and space constraints must be considered.

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is a 6 cm w_0 gaussian beam for both ITM and ETM.

All thermal noise calculations depend on the test mass size and material. We assume a sapphire test mass with dimensions: mass, 40 kg; diameter, 31.4 cm; thickness, 13 cm. If fused silica is instead chosen for the test mass some requirements will need revision.

3.2.1.2 Noise performance

Table 1: Noise performance requirements, test mass suspensions

Parameter	Value	Discussion
Longitudinal thermal noise due to test mass internal modes	5×10^{-20} m/√Hz at 10 Hz, falling roughly as 1/f	Figure 1; see section 3.2.1.2.1.
Longitudinal thermal noise due to pendulum motion	10^{-19} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	See section 3.2.1.2.2.
Pitch noise	5×10^{-18} rad/√Hz at 10 Hz, falling roughly as (1/f)	Requirement driven by offset of beam from center of mirror, alignment servo gain
Yaw noise	5×10^{-18} rad/√Hz at 10 Hz, falling roughly as (1/f)	Requirement driven by offset of beam from center of mirror, alignment servo gain
Vertical transverse thermal noise	10^{-16} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Assumes vertical to longitudinal motion coupling of 10^{-3}
Horizontal transverse thermal noise	1×10^{-17} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Based on .001 coupling to longitudinal motion
Longitudinal technical noise	1/10 of thermal noise above lower-frequency cutoff	
Vertical transverse technical noise	1/10 of thermal noise above lower-frequency cutoff	

Horizontal transverse thermal noise	1/10 of thermal noise above lower-frequency cutoff	

3.2.1.2.1 Longitudinal displacement, internal thermal modes

The internal thermal noise performance can be divided into 'intrinsic' and 'extrinsic' categories. The intrinsic sources of thermal noise derive from mechanisms which are (presumably) beyond experimental improvement, such as the internal losses and thermoelastic effects in the test mass material, although the size and shape of the mass and reflected beam will influence the observed thermal noise. The polish and reflective coating on the mirror, though an active field of research at present, may also prove to be intrinsic by this definition. Intrinsic noise is an input parameter to the suspension design. The extrinsic sources of noise derive from things that are done to the test masses, such as attachment to the suspension. We require that the extrinsic sources of noise not significantly increase the thermal noise set by the intrinsic sources where internal thermal noise limits interferometer sensitivity.

The following internal thermal noise spectrum assumes a 40 kg sapphire mass with 5×10^{-9} loss factor, and was made using Bench version 1.7 and Cagnoli's Maple thermal noise model. Coating and polishing losses are not considered in this spectrum and are not considered intrinsic noise sources for the purposes of setting these requirements.

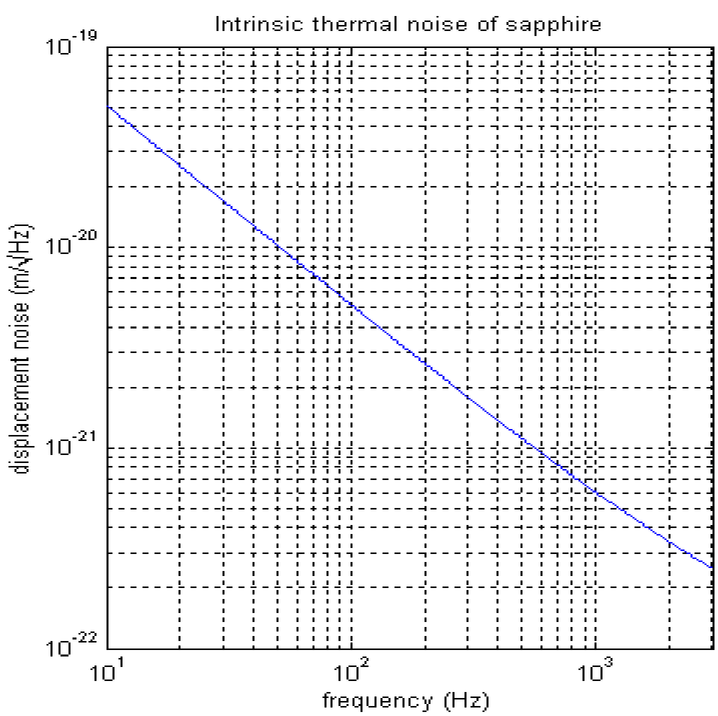

Figure 1: Intrinsic thermal noise of sapphire test mass

3.2.1.2.2 Longitudinal displacement, pendulum suspension thermal noise

Pendulum thermal noise is not expected to dominate over optical noise, but can be comparable if the IFO is operated at low laser power and fibers are chosen to suspend the optic. For this reason, fused silica fibers are assumed to be used instead of ribbons, but this is not a requirement, and ribbons may be used if research proves their superior performance, reliability, and ease of use.

3.2.1.2.3 Pitch noise

Pitch and yaw noise are special in that LIGO will use alignment sensing and control to reduce these noise sources independently of the longitudinal sensing and control. Therefore these requirements are not on the SUS alone but in combination with ISC. All sources of noise- thermal, seismic, technical- and the alignment servo together must not lead to pitch noise in excess of the quoted requirement.

The energy in this mode is stored in tension in the suspension fibers (or in the twists of a ribbon) and the losses may be large. The coupling to pitch depends on the position of the optical beam; for a specific suspension design, there is a point which will give minimum coupling (Ref: Levin). The technical noise will also have a position-dependent coupling and the two optima may not be in the same place; to be considered in the technical requirements. The value of allowed angular noise is traded against the positioning accuracy; the specification quoted in the table assumes centering within 1mm, and gives an equivalent thermal noise power 10x lower than the longitudinal thermal noise. In truth, should the thermal noise in this or any other angular degree of freedom threaten the longitudinal noise requirement, then the requirement effectively restricts the positioning accuracy.

Pitch noise of the ITM will also couple into the power and signal recycling cavities. However, the pitch noise requirement listed above is more stringent than for the other mirrors in those cavities.

3.2.1.2.4 Yaw noise

The discussion of alignment servoes in the section on pitch noise is also relevant here.

The energy in this mode is largely stored in the gravitational field and thus the losses can be small. Again, the positioning of the beam is important and this requirement needs to be set along with a centering precision. However, as opposed to the case for pitch the point of minimum coupling will be at middle of the mirror. The specification quoted in the table assumes centering within 1mm, and gives an equivalent thermal noise power 10x lower than the longitudinal thermal noise.

As with pitch noise, yaw noise of the ITM will also couple into the power and signal recycling cavities. However, the yaw noise requirement listed above is more stringent than for the other mirrors in those cavities.

3.2.1.2.5 Vertical transverse thermal noise

The LIGO beams are a maximum of 6×10^{-4} rad away from local vertical, making this the minimum coupling from vertical to longitudinal thermal noise. Practical experience leads to an anticipation of 10^{-3} coupling from vertical to horizontal. We require that the vertical contribution be equal or less than the longitudinal contribution, allowing 10^{3} more noise in the vertical or $\sim 10^{6}$ greater loss. For the ITM, which is a transmissive optic likely to have a vertical wedge, vertical transverse thermal noise will also couple to longitudinal noise in the short degrees of freedom (power recycling cavity, signal cavity, Michelson fringe). The requirement based on this coupling is about 2×10^{-15} m/√Hz at 10 Hz (assuming a coupling of vertical to horizontal motion of .01 outside the arm cavity due to the optic wedge) and so is less stringent by far. This noise power is not required to be smaller than the longitudinal thermal noise by a safety factor because it is expected to be an intrinsic noise source.

Additionally, the frequency of the vertical bounce mode shall be below 10Hz.

3.2.1.2.6 Horizontal transverse thermal noise

In the horizontal transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on an assumed .001 coupling of horizontal transverse to longitudinal motion. This requirement will require review if the ITM's have horizontal wedges due to coupling to the power and signal cavities.

3.2.1.2.7 Longitudinal displacement technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal noise. Sources of technical noise include but are not restricted to: sensor and actuator noise, stray electric charges on the test mass or suspension, ambient magnetic field fluctuations at the magnetic actuators, and excess noise due to creep events in the suspension materials. It is noted that stray charge on the mass can increase pendulum thermal noise by coupling with nearby conductors.

3.2.1.2.8 Transverse technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal noise for the given transverse to longitudinal coupling. The sources of technical noise listed in 3.2.1.1.6 are also relevant here.

3.2.1.3 Seismic isolation performance

The seismic isolation will be determined by the pendulum lengths and blade spring frequencies; these will be chosen to give the best thermal noise performance and to make the system mode coupling best for the local damping system within the mechanical constraints. Thus, the suspension design dictates the suspension isolation. However, given that the remainder of the isolation is provided by the SEI, which have frozen their requirements at some point, the isolation given by the conceptual design then becomes a requirement for SUS. The test mass motion due to seismic noise will depend on numerous couplings of the six degrees of freedom of the platform motion to the six degrees of freedom of the test mass. Rather than enumerate them all we instead specify the seismic motion requirements at the test mass, given the platform noise spectrum given in the Seismic Isolation Subsystem Design Requirements Document LIGO-E990303-03-D. Note that the longitudinal seismic noise requirement at 10Hz equals that of thermal noise. The seismic noise at higher frequencies will be much less than thermal noise due to the greater rolloff. The seismic isolation requirements arrived at by this process are given in the following table:

Table 2: Isolation performance requirements, test mass suspensions

Longitudinal	10^{-19} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Horizontal transverse	3.3×10^{-17} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	Assumes horizontal transverse to longitudinal motion coupling of 10^{-3}
Vertical transverse	3.3×10^{-17} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	Assumes vertical to longitudinal motion coupling of 10^{-3}

The specified frequency rolloff of the seismic noise at the suspension is conservative and should easily be achieved by the combined SEI-SUS system. It is chosen to guarantee that seismic noise falls off much more rapidly with frequency than thermal noise.

3.2.1.4 Control performance

The control performance requirements, broadly stated, are that the suspension be capable of acquiring lock as part of a globally controlled advanced LIGO configuration, with the arm cavity powers and dynamic characteristics appropriate for the laser powers and arm cavity finesses set by the systems group, and that with the SEI it should provide sufficient dynamic range and bandwidth to control the locked interferometer during operation. The SEI will provide large actuation range at low frequency (≤100mHz).

The local damping shall be tunable, and be able to reduce the ringdown time of all body modes (save vertical bounce and roll of the bottom mass) to less than 10 seconds. The local damping shall have the option of being switched off. Sensor noise related to the local damping is discussed as a technical noise source in section 3.2.1.2.7.

All DOF sensors and all DOF actuators are to be accessible to the suspension control system, with the potential of frequency-dependent cross-coupling terms.

The control (and entire) system will perform correctly for angles of the mounting table of up to 100 microrad (TBR).

3.2.2 Performance Characteristics: Recycling Mirror Suspensions

The recycling mirror suspension system is mounted (via bolts and/or clamps) to the HAM seismic isolation system by attachment atop the HAM SEI optics table. Available height above the optics table may prove to be a tight constraint.

The recycling mirror suspensions have much less stringent requirements than the test mass suspensions and are not expected to participate in any systems design tradeoffs. However, the requirements from systems design could change, most probably the diameter of the recycling mirror. Furthermore, though the performance requirements of the signal recycling mirror are slightly more stringent than those of the power recycling mirror, the two recycling mirrors will have identical dimensions and materials, and in the interest of common design the signal recycling mirror requirements are adopted for both mirrors.

Because these requirements are expected to be easily achievable, all sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

3.2.2.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0.

All thermal noise calculations depend on the recycling mirror size and material. We assume a fused silica mirror with dimensions: m = 12.2 kg, diameter = 26.5 cm, thickness = 10 cm.

3.2.2.2 Noise performance

Table 3: Noise performance requirements, recycling mirror suspensions

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	$4x10^{-16}$ m/√Hz at 10 Hz, falling to $1.5x10^{-17}$ m/√Hz at 100 Hz	See section 3.2.2.2.1 and the seismic isolation requirements
Pitch noise	$4.4x10^{-14}$ rad/√Hz at 10 Hz, falling to $1.7x10^{-15}$ rad/√Hz at 100 Hz	Requirement driven by optical path length through wedged ITM
Yaw noise	$2.7x10^{-14}$ rad/√Hz at 10 Hz, falling to $1x10^{-15}$ rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter
Vertical transverse displacement noise	$2.2x10^{-13}$ m/√Hz at 10 Hz, falling to $8.3x10^{-15}$ m/√Hz at 100 Hz	Assumes coupling of vertical to longitudinal motion of .0018; see section 3.2.2.2.4
Horizontal transverse noise	$4x10^{-13}$ m/√Hz at 10 Hz, falling to $1.5x10^{-14}$ m/√Hz at 100 Hz	See section 3.2.2.2.5

3.2.2.2.1 Longitudinal displacement

The longitudinal displacement noise requirement for the signal recycling mirror is driven by the generation of noise sidebands directly onto the output GW signal. Assuming the RF readout scheme, which is more sensitive to the signal recycling mirror motion than the DC readout scheme, and comparing sensitivity to SRM motion to that of end mirror motion leads to the quoted specs (see document T010097-00-D).

The longitudinal displacement noise requirement for the power recycling mirror is driven by the frequency stability requirements of the laser, which uses the interferometer itself as a reference cavity. These requirements are $6x10^{-7}$ Hz/√Hz at 10Hz and $1.9x10^{-7}$ Hz/√Hz at 100Hz. Translating these frequency noise requirements to displacement requirements for the power recycling mirror and including a safety factor so that the recycling mirror does not dominate the noise budget leads to the power recycling mirror requirements, which are nearly equal to the SRM requirements at 10Hz and 100Hz but slightly higher in between (again, see document T010097-00-D).

3.2.2.2.2 Pitch noise

Assuming the beam will be centered on the optic only to within 5mm, there will be a pitch to longitudinal displacement coupling of .005 m/rad due to motion of the reflecting surface of the recycling mirror.

Inhomogeneities in the refractive index of the material are expected to lead to optical path variations of about 10nm per mm of transverse motion of the beam through the ITM's and beamsplitter. The maximum wedge of 3 degrees in the ITM gives a larger ~$5x10^{-7}$ m optical path length change per mm of transverse motion. Given cavity lengths of ~8m, a tilt of $1.3x10^{-4}$ rad will give 1mm transverse displacement at the ITM, thus the coupling will be $4x10^{-3}$ m/rad, which is comparable to the .005 m/rad coupling caused by a 5mm offset of the beam from the center of the optic. These couplings are estimated without considering coupled cavity effects, which are likely to reduce them somewhat. Nevertheless, the most conservative approach would be to combine the couplings derived here, which is what we have done.

3.2.2.2.3 Yaw noise

This requirement has the same considerations as pitch noise. In addition, the first-order dependence of path length on transmission angle through the beamsplitter leads to a coupling of ~.01 m/rad, which also might be reduced by coupled cavity effects. The sum of this coupling and that from a 5mm beam offset from optic center is adopted as setting the requirement for yaw motion.

3.2.2.2.4 Vertical transverse noise

The ITM's are likely to have vertical wedges, which will lead to a much larger coupling of vertical motion to longitudinal motion in the recycling mirrors than in the ITM's. The requirement quoted assumes a coupling of .0018 as given in Table 8 of LIGO-T010076-01-D. If the ITM's instead have wedges such that the beam travels horizontally when incident on the recycling mirror, the vertical coupling can be assumed to drop to .001 based on practical experience with unintended vertical-to-horizontal cross-couplings.

The frequency of the vertical bounce mode is not required to be below 10Hz. However, any isolated noise peaks due to the vertical bounce must be sufficiently narrow where they appear in the IFO output spectrum that they are easily filtered without substantial loss of detector bandwidth.

3.2.2.2.5 Horizontal transverse noise

In the horizontal transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be .001. This does not change if the wedges in the ITM's are horizontal rather than vertical.

3.2.2.3 Seismic isolation performance

Seismic noise is included in the noise requirements above. Any peaks in the isolation, for example those due to resonances in blade springs, must not increase the displacement noise above the requirements quoted in Table 3 when considered in combination with the input seismic noise spectrum from the SEI system. The interchangeability of vertical and horizontal transverse motion mentioned in section 3.2.2.2.5 also applies here.

3.2.2.4 Control performance

The control performance requirements for the recycling mirrors are the same as those for the test mass suspensions.

3.2.3 Performance Requirements: Beamsplitter Suspensions

The beamsplitter suspension system is mounted (via bolts and/or clamps) to the BSC seismic isolation system by attachment below the BSC SEI optics table.

The beamsplitter suspensions have much less stringent requirements than the test mass suspensions and are not expected to participate in any systems design tradeoffs. Because these requirements are expected to be easily achievable, all sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

3.2.3.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0.

All thermal noise calculations depend on the beamsplitter size and material. We assume a fused silica mirror with dimensions: m = 12.7 kg, diameter = 35 cm, thickness = 6 cm.

3.2.3.2 Noise performance

Table 4: Noise performance requirements, beamsplitter suspensions

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	2×10^{-17} m/√Hz at 10 Hz, falling to 6×10^{-19} m/√Hz at 100 Hz	See section 3.2.3.2.1
Pitch noise	2.9×10^{-15} rad/√Hz at 10 Hz, falling to 8.6×10^{-17} m/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror and ITM vertical wedge; See section 3.2.3.2.2
Yaw noise	1.3×10^{-15} rad/√Hz at 10 Hz, falling to 4×10^{-17} rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter; See section 3.2.3.2.3
Vertical transverse displacement noise	2.2×10^{-15} m/√Hz at 10 Hz, falling to 6.7×10^{-17} m/√Hz at 100 Hz	Assumes vertical to longitudinal motion coupling of .009; see section 3.2.3.2.4
Horizontal transverse noise	2×10^{-14} m/√Hz at 10 Hz, falling roughly as 1/f	See sections 3.2.3.2.5

3.2.3.2.1 Longitudinal displacement

The longitudinal displacement noise requirement is driven by the need to maintain the dark fringe at the output port. Since the beamsplitters are not in the arm cavities, they can be noisier than the test masses by a factor equal to the arm cavity phase gain, corrected to account for the 45° incident angle, and with another factor of 3.5 as a safety margin.

These requirements are so much less stringent than the requirements for the test masses that they are expected to be easily achievable and thus not involve detailed performance tradeoffs. Therefore, all sources of noise are included in this requirement, including seismic noise.

3.2.3.2.2 Pitch noise

Pitch noise leads to displacement noise if the beam is offset above or below the center of the mass, so this requirement needs to be set along with a centering precision. The specification quoted in the table assumes centering within 5mm.

Additionally, the presence of a vertical wedge in the ITM (maximum value 3 degrees) causes a variation in optical path of a ~$5x10^{-7}$ m optical path length change per mm of transverse motion. Given a BS/ITM separation of ~4m, a tilt of $7x10^{-5}$ rad will give 1mm transverse displacement at the ITM, thus the coupling will be $2x10^{-3}$ m/rad, which is comparable to the .005 m/rad coupling caused by a 5mm offset of the beam from the center of the optic. This coupling is estimated without considering coupled cavity effects, which are likely to reduce it somewhat. Nevertheless, the most conservative approach would be to assume the sum of these couplings in setting the pitch requirement, which is what we have done here.

3.2.3.2.3 Yaw thermal noise

This requirement has the same considerations as pitch noise. In addition, the first-order dependence of path length on transmission angle through the beamsplitter leads to a coupling of ~.01 m/rad, which also might be reduced by coupled cavity effects. The sum of these couplings is adopted as setting the requirement for yaw motion.

3.2.3.2.4 Vertical transverse noise

The vertical wedges in the ITM's will also limit the vertical transverse motion of the beamsplitter as well as the recycling mirrors. The requirement quoted assumes a coupling of .014 as given in Table 8 of LIGO-T010076-01-D. If the ITM's instead have wedges such that the beam travels horizontally when incident on the beamsplitters, the vertical coupling can be assumed to drop to .001 based on practical experience with unintended vertical-to-horizontal cross-couplings.

The frequency of the vertical bounce mode is required to be below 10Hz, and any isolated noise peaks due to the violin resonances must be sufficiently narrow where they appear in the IFO output spectrum that they are easily filtered without substantial loss of detector bandwidth.

3.2.3.2.5 Horizontal transverse noise

In the horizontal transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be .001. This will not change if the wedges in the ITM's are horizontal rather than vertical.

3.2.3.3 Seismic isolation performance

As with the thermal noise requirements, the specified seismic noise requirements are much less stringent than for the test mass suspensions and should easily be achieved by the beamsplitter suspensions. These requirements scale from the test mass requirements in the same way as the thermal noise requirements. Any peaks in the isolation, for example those due to resonances in blade springs, must not increase the displacement noise above the requirements quoted in Table 4 when considered in combination with the input seismic noise spectrum from the SEI system as given in LIGO document LIGO-E990303-03-D. The interchangeability of vertical and horizontal transverse motion mentioned in section 3.2.3.2.5 also applies here.

3.2.3.4 Control performance

The control performance requirements are the same as those for the test mass suspensions.

3.2.4 Performance Requirements: Folding Mirror Suspensions

The folding mirrors referred to here are those suspended beneath the BSC SEI platform of the folded interferometer along with the input test masses. Because of this the weight and size of the folding mirror suspensions and input test mass suspensions together must not exceed weight or space constraints under the BSC SEI optics table

The folding mirror suspensions have much less stringent requirements than the test mass suspensions and are not expected to participate in any systems design tradeoffs. However, the requirements from systems design could change; for example, the radius is linked to that of the test mass, which will change if fused silica is chosen for the test mass material. Because these requirements are expected to be easily achievable, all sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

3.2.4.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0.

All thermal noise calculations depend on the folding mirror size and material. We assume a fused silica mirror with dimensions: m = 25 kg, diameter = 35 cm, thickness = 11.8 cm.

3.2.4.2 Noise performance

Table 5: noise performance requirements, folding mirror suspensions

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	2×10^{-17} m/√Hz at 10 Hz, falling to 6×10^{-19} m/√Hz at 100 Hz	See section 3.2.4.2.1 and the seismic isolation requirements
Pitch noise	4×10^{-15} rad/√Hz at 10 Hz, falling to 1.2×10^{-16} rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror
Yaw noise	1.3×10^{-15} rad/√Hz at 10 Hz, falling to 4×10^{-17} rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter
Vertical transverse displacement noise	TBD	Vertical to longitudinal motion coupling TBD; see sections

		3.2.4.2.4-5
Horizontal transverse noise	2×10^{-14} m/√Hz at 10 Hz, falling to 6×10^{-16} m/√Hz at 100 Hz	See sections 3.2.4.2.4-5

3.2.4.2.1 Longitudinal displacement

The longitudinal displacement noise requirement for the folding mirrors, like that of the beamsplitters, is driven by the need to maintain the dark fringe at the output port. Since the folding mirrors are not in the arm cavities, they can be noisier than the test masses by a factor equal to the arm cavity phase gain, corrected to account for the 45° incident angle, and with another factor of 3.5 as a safety margin.

These requirements are so much less stringent than the requirements for the test masses that they are expected to be easily achievable and thus not involve detailed performance tradeoffs. Therefore, all sources of noise are included in this requirement, including seismic noise.

3.2.4.2.2 Pitch noise

This requirement is based on beam centering. If the beam is offset from the center of the folding mirror vertically, then small tilts of the mirror will change the path length of the laser beam from the beamsplitter to the input test mass to first order. The coupling due to the wedge in the ITM, which dominates the pitch noise coupling for the recycling mirrors and beamsplitter, is negligible for the folding mirrors since they are less than a meter away from the ITM's. The centering is assumed to be within 5mm.

3.2.4.2.3 Yaw thermal noise

This motion couples most strongly into the displacement noise through the dependence of the optical path length through the beamsplitter on incident angle. The beam passing through the 6cm thick beamsplitter sees a coupling of ~.01 m/rad. This coupling is added to that due to the 5mm beam offset from the mirror center.

3.2.4.2.4 Vertical transverse noise

The vertical wedges of the ITM's limit the allowable vertical motion of the folding mirrors as well. The requirement depends upon a coupling which is TBD. If the ITM's instead have wedges such that the beam travels horizontally when incident on the folding mirrors, the vertical coupling can be assumed to drop to .001 based on practical experience with unintended vertical-to-horizontal cross-couplings.

The frequency of the vertical bounce mode is required to be below 10Hz, and any isolated noise peaks due to the violin resonances must be sufficiently narrow where they appear in the IFO output spectrum that they are easily filtered without substantial loss of detector bandwidth.

3.2.4.2.5 Horizontal transverse noise

In the horizontal transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be .001. This does not change if the wedges in the ITM's are horizontal rather than vertical.

3.2.4.3 Seismic isolation performance

As with the thermal noise requirements, the specified seismic noise requirements are much less stringent than for the test mass suspensions and should easily be achieved by the folding mirror suspensions. These requirements scale from the test mass requirements in the same way as the thermal noise requirements. Any peaks in the isolation, for example those due to resonances in blade springs, must not increase the displacement noise above the requirements quoted in Table 5 when considered in combination with the input seismic noise spectrum from the SEI system. The interchangeability of vertical and horizontal transverse motion mentioned in section 3.2.4.2.5 also applies here.

3.2.4.4 Control performance

The control performance requirements are the same as those for the test mass suspensions.

3.2.5 Performance Requirements: Mode Cleaner Suspensions

There will be two suspended mode cleaners within the HAM chambers: an input mode cleaner before the mode-matching telescope and an output mode cleaner after the signal recycling mirror. These requirements are specifically for the input mode cleaner mirrors. The output mode cleaner mirror suspensions are assumed to be identical pending a detailed systems review.

The input mode cleaner mirror suspension system is mounted (via bolts and/or clamps) to the HAM seismic isolation system by attachment above the HAM SEI optics table.

All sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

3.2.5.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 1 mm w_0.

All thermal noise calculations depend on the input mode cleaner mirror size and material. We assume a fused silica mirror with dimensions: m = 3.5 kg, diameter = 15.8 cm, thickness = 7.9 cm.

3.2.5.2 Noise performance

Table 6: Noise performance requirements, mode cleaner mirror suspensions

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	3×10^{-17} m/√Hz at 10 Hz, falling to 3×10^{-19} m/√Hz at 100 Hz	See section 3.2.5.2.1
Pitch noise	3×10^{-14} rad/√Hz at 10 Hz, falling to 3×10^{-16} rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror
Yaw noise	3×10^{-14} rad/√Hz at 10 Hz,	Requirement driven by offset

	falling to $3x10^{-16}$ rad/√Hz at 100 Hz	of beam from center of mirror
Vertical transverse displacement noise	$3x10^{-14}$ m/√Hz at 10 Hz, falling to $3x10^{-15}$ m/√Hz at 100 Hz	Assumes vertical to longitudinal motion coupling of .001; see sections 3.2.5.2.4
Horizontal transverse noise	$3x10^{-14}$ m/√Hz at 10 Hz, falling to $3x10^{-15}$ m/√Hz at 100 Hz	See sections 3.2.5.2.5

3.2.5.2.1 Longitudinal displacement

The longitudinal displacement noise requirement is driven by the need for the mode cleaner not to introduce frequency noise into the light transmitted through it.

These requirements are less stringent than the requirements for the test masses; however, given the limited space within the HAM chambers, the required seismic isolation may be difficult to obtain, and given the small beam size on the optic, the internal thermal noise may be large.

3.2.5.2.2 Pitch noise

This requirement is based on coupling of tilt to displacement motion when the beam is not centered on the optic. Assuming the beam is centered within 1mm, the displacement noise is as specified.

3.2.5.2.3 Yaw thermal noise

This requirement is based upon the same considerations as for pitch noise.

3.2.5.2.4 Vertical transverse noise

The mode cleaner is short and can have the input and output beams horizontally aligned. Therefore, the requirement quoted assumes a vertical to horizontal coupling of .001 based upon experience with achievable levels of residual coupling.

The frequency of the vertical bounce mode is not required to be below 10Hz, but any isolated noise peaks due to the suspension fiber resonances must be sufficiently narrow where they appear in the IFO output spectrum that they are easily filtered without substantial loss of detector bandwidth.

3.2.5.2.5 Horizontal transverse noise

In the horizontal transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be .001.

3.2.5.3 Seismic Isolation Performance

As with the thermal noise requirements, the specified seismic noise requirements are much less stringent than for the test mass suspensions and should easily be achieved by the mode cleaner mirror suspensions. These requirements scale from the test mass requirements in the same way as the thermal noise requirements. Any peaks in the isolation, for example those due to resonances in blade springs, must not increase the displacement noise above the requirements quoted in Table 6 when considered in combination with the input seismic noise spectrum from the SEI system as given in LIGO document LIGO-E990303-03-D. The interchangeability of vertical and horizontal transverse motion mentioned in section 3.2.3.2.5 also applies here.

3.2.5.4 Control performance

The control performance requirements are the same as those for the test mass suspensions.

3.2.6 Interface Requirements

3.2.6.1 Interfaces to other LIGO detector subsystems

3.2.6.1.1 Mechanical Interfaces

3.2.6.1.1.1 Auxiliary Optics

SUS will receive requirements from AOS for points of attachment on the suspension 'cage' for light baffles.

3.2.6.1.1.2 Core Optics

The dimensions of the optics are the primary interface between COC and SUS. This includes any wedges in the optics and all flat surfaces polished into the optics for attachments to the suspension. These dimensions are partially specified by SUS with respect to attachment needs. Flatness and polish requirements for the attachment surfaces will be given to COC by SUS and are not specified here.

Coatings required for actuation (e.g. an electrostatic drive) are part of the SUS design.

3.2.6.1.1.3 Seismic Isolation

The suspension should be capable of attachment to the SEI platform via the bolt holes provided therein. The weight of the suspension combined with any other suspensions, auxiliary optics, and counterweights that share the same SEI platform must not exceed the 800kg limit set by the SEI design. This requirement will be pushed hardest by the combination of ITM and FM suspensions in the folded IFO.

The moments of inertia of the suspension will be given to SEI as a design parameter.

The suspension cabling should have provision for attachment to the SEI platform.

3.2.6.1.2 Electrical Interfaces

3.2.6.1.2.1 AOS

SUS will give requirements to AOS for the bandwidth and dynamic range of the photon drive actuator. These requirements are not specified here.

3.2.6.1.2.2 Core Optics

Any grounding of core optics will be through cabling attached to the suspension chain.

3.2.6.1.2.3 Seismic Isolation

All electrical cabling from the suspension to outside the vacuum envelope will anchor to the SEI platform.

See also section 3.2.6.3.1.

3.2.6.1.3 Optical Interfaces

3.2.6.1.3.1 AOS

The suspension will provide a clear aperture for any IFO laser paths, including any wedge and ghost beams reflecting from the optics as required by systems design. It will also provide clear apertures for the photon actuator and optical lever beams. The local sensors will not be susceptible to light from the photon actuator or optical lever at a level that would disrupt control or introduce technical noise above the levels specified.

Scatter from the suspension frame surfaces is not expected to be a significant source of noise in the detector and so no requirements are made on their reflectivity or perpendicularity.

3.2.6.1.3.2 Core Optics

The suspension will not obstruct the main IFO beam. The ETM reaction mass may partially obstruct any transmitted monitor field at a level that is TBD; the ITM reaction mass, if any, must not introduce reflective or diffractive loss above the levels of losses elsewhere in the short cavities of the IFO.

The local sensors will not be susceptible to light from the IFO at a level that would disrupt control or introduce technical noise above the levels specified.

3.2.6.2 Interfaces external to LIGO detector subsystems

The suspensions for the folded IFO shall not obstruct the 4K IFO beams.

3.2.6.3 Induced Electromagnetic Radiation

3.2.6.3.1 Magnetic fields emitted

The magnetic motors shall not generate fields that will compromise the seismic isolation system sensors (which are coil-and-magnet technology).

3.2.6.3.2 Magnetic field susceptibility

The magnetic environment must be such that the induced motion in the highest suspension stage carrying permanent magnets is significantly smaller than the residual seismic motion without the fields. The seismic isolation system actuators generate fields.

3.3 Precedence

Those requirements relating to thermal noise in the test masses have the highest priority. Compromises in the seismic isolation or the actuation can be more probably compensated in other subsystems.