Suspension Design Requirements Review

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Suspension Design Requirements Review

Agenda

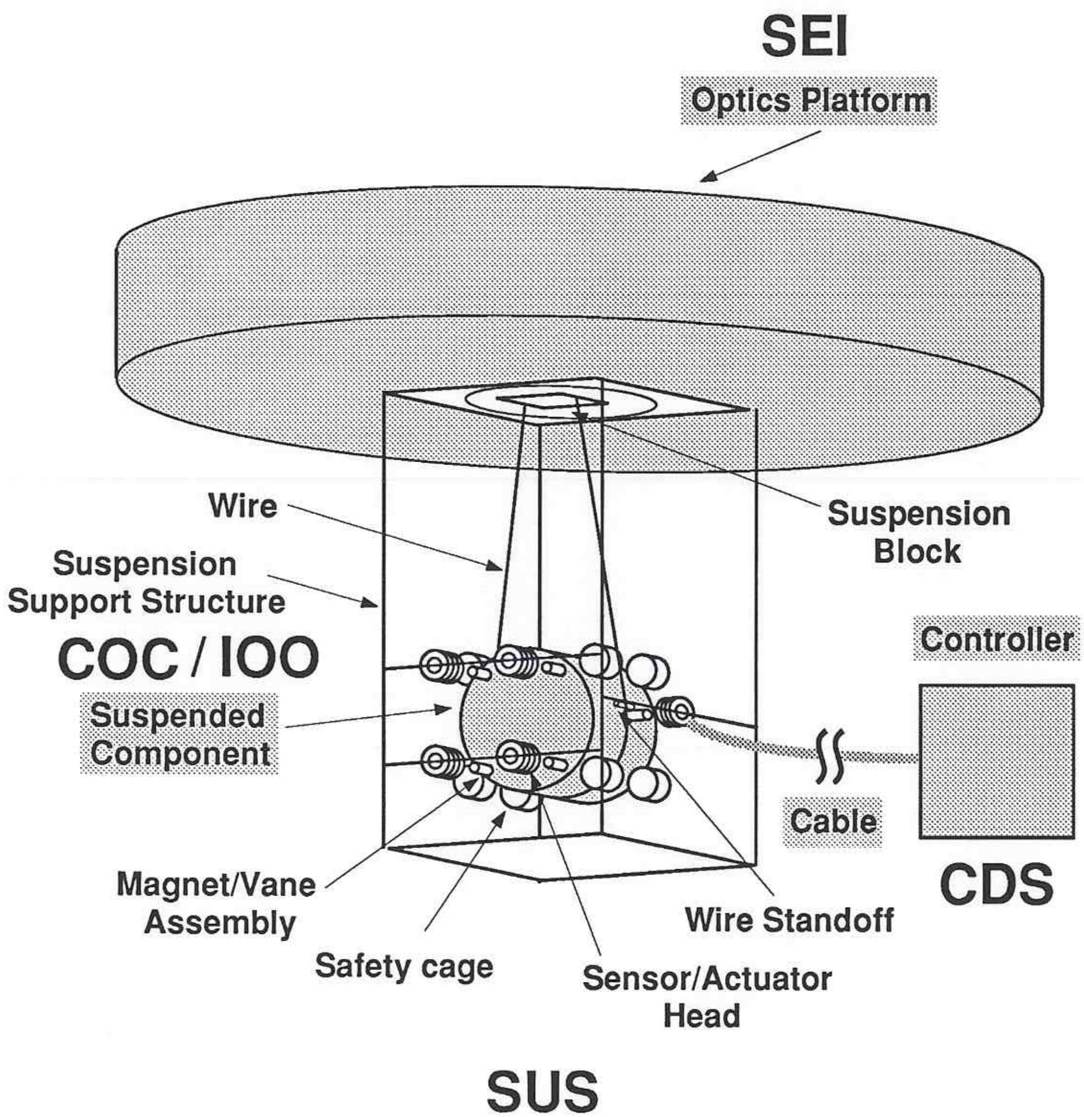
- Charge and Introduction (WEA) *p.3 - p.6*
- System Definition (30 minutes) *p.7 - p.23*
- Design Requirements (2 hour) *p.24 - p.26*
- Interfaces (30 minutes) *p.24 - p.26*
- Conceptual Design (1 hour) *p.27 - p.36*
- Testing Criteria (30 minutes) *p.37 - p.46*
- Implementation (10 minutes) *p.47*
- Discussion of SUS DRD (1 hour)

Change from DRD

Functional Definition

- Suspend a test mass to allow it to move freely horizontally for detection of gravitational waves.
- Isolate an optical component from ground motion by suspending the component.
- Damp the optical component's motion in position and orientation using the local suspension's sensors and actuators.
- Provide control inputs for applying forces and torques to the suspended component in response to signals from the LSC and ASC systems.
- Protect the optical components by limiting motion from external disturbance.
- Reduce the effect of stray/scattered light from the optical component.

Physical Definition



Stray Light Shield
Suspension Platform

Large Optics Suspension and Small Optics Suspension

- Three kinds of suspension (LOS 1, LOS 2, SOS) for three kinds of optical components ?
- Adaptor for thinner components ?

List of suspended optical components

SUS type	*Suspended Optical Components*
LOS 1	Test Masses (CO), Recycling Mirror (CO), Large Mode Matching Mirror (IOO) **TBD**, Faraday Isolator (IOO), Pockels cell (IOO) **TBD**, Large Fold Mirrors (CO), Pick-offs (CO) **TBD**, Large Steering Mirrors (IOO) **TBD**
LOS 2	Beamsplitter (CO)
SOS	Mode Cleaner Mirrors (IOO), Small Steering Mirrors (IOO), Small Mode Matching Mirror (IOO)

Damping by Suspension's Sensor

States of interferometer operation in which optical components are damped by the suspension's sensor

Motion	*TM*	*BS, RM, MCM, FM,SM MMM*	*Pick-off* ***TBD,*** *FI, PC* ***TBD***
Longitudinal	Before and during acquisition	Always	Always
Transverse	Always	Always	Always
Orientation	Before acquisition	Before acquisition	Always

Size Requirements

- Suspension system must accommodate the corresponding optical component.
- Size of the suspension system ? **TBD**

Size and stay-clear.

Physical Quantity	*TM*	*BS*	*MCM*
Diameter	25 cm	30 cm **TBR**	7.5 cm
Thickness	10 cm	10 cm **TBR**	2.5 cm **TBR**
Weight	11 kg	16 kg **TBR**	0.3 kg **TBR**
Stay-clear	20 cm (ETM) 12 cm (ITM)	12 cm (45º, offset from center) **TBR**	**TBD**

Beam Height

- The suspension system must provide a proper vertical position for the suspended components.

Beam height.

Physical Quantity	*TMC Chamber*	*BSC Chamber*	*HAM Chamber*
Beam Height	-60.0 cm from bottom surface of optics platform	-60.0 cm from bottom surface of optics platform	+20 cm from top surface of stack top plate

Longitudinal Motion Dynamic Range of Actuator in Operation

No Saturation in the actuator driver longitudinally in the operation mode.

For Example...

- Required dynamic range is $3\times10^{-9}\,\mathrm{m_{pp}}$ for test mass at 10 Hz with a bandwidth of 10 Hz

  ››The seismically ~~excited test mass mo~~tion is dominant in the feedback signal.

  ››The ground motion is $3\times10^{-9}\,\mathrm{m_{rms}}$.

  ››The pendulum transfer function is 1×10^{-2}.

  ››The stack transfer function is 3.

  ››Therefore the test mass motion is $1\times10^{-10}\,\mathrm{m_{rms}}$.

  ››Multiply it by $30 = 3\,(\mathrm{rms} \Rightarrow \mathrm{pp}) \times 10\,(\mathrm{statistic \cdot factor})$.

Longitudinal Motion Dynamic Range of Actuator in Operation

Dynamic range requirements

Physical Quantity	*Requirement*			*Unit (Freq.)*
	TM	*BS*	*MCM*	
Longitudinal Motion Dynamic Range of Actuator in Operation	$>1\times10^{-5}$	$>1\times10^{-6}$ TBR	$>1\times10^{-5}$	m_{pp} (0.1 Hz)
	$>3\times10^{-8}$	$>3\times10^{-8}$	$>3\times10^{-8}$	m_{pp} (1 Hz)
	$>3\times10^{-9}$	$>1\times10^{-9}$	$>3\times10^{-9}$	m_{pp} (10 Hz)
	$> 6\times10^{-17}$	Trivial	$> 6\times10^{-17}$	m_{pp} (100 Hz)
	$> 3\times10^{-16}$	Trivial	$> 3\times10^{-16}$	m_{pp} (1 kHz)

Longitudinal Motion Dynamic Range of Actuator in Acquisition

TBR

- The dynamic range for the 40m interferometer as a start.

Dynamic range requirements

Physical Quantity	*Requirement*			*Unit (Freq.)*
	TM	*BS*	*MCM*	
Longitudinal Motion Dynamic Range of Actuator in Acquisition **TBR**	$>3\times10^{-5}$	N/A	**TBD**	m_{pp} (0.1 Hz)
	$>3\times10^{-5}$			m_{pp} (1 Hz)
	$>3\times10^{-7}$			m_{pp} (10 Hz)
	$>3\times10^{-9}$			m_{pp} (100 Hz)
	$>3\times10^{-11}$			m_{pp} (1 kHz)

Orientation Dynamic Range of Actuator

No Saturation in the actuator driver for orientation control.

For Example...

- Required dynamic range is $2 \times 10^{-3} m_{pp}$ for test mass at DC.
  - ››Expected drift is?.

Orientation Dynamic Range of Actuator

Dynamic range requirements

Physical Quantity	Requirement			Unit (Freq.)
	TM	BS	MCM	
Orientation Dynamic Range of Actuator	$>2\times10^{-3}$	$>2\times10^{-3}$	$>4\times10^{-3}$	rad_{pp} (DC)
	$>6\times10^{-7}$	$>6\times10^{-7}$	$>6\times10^{-7}$	rad_{pp} (0.1 Hz)
	$>2\times10^{-7}$	$>2\times10^{-7}$	$>2\times10^{-7}$	rad_{pp} (1 Hz)
	$> 6\times10^{-10}$	$> 6\times10^{-10}$	$> 6\times10^{-10}$	rad_{pp} (10 Hz)

System-level Noise Requirements

- Non-primary noise (~ ten kinds totally) must be lower than the LIGO sensitivity by a factor of 10 per kind.

System-level noise requirements

Noise per Mass	*Requirement*			*Unit (Freq.)*
	TM	*BS*	*MCM*	
Thermal Noise	$< 7\times10^{-20}$	$< 1.4\times10^{-18}$	<**TBR** 6×10^{-18}	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (100 Hz)
Seismic Noise	$< 5\times10^{-19}$	$< 1\times10^{-17}$	<**TBR** 1.2×10^{-15}	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (40 Hz)
Control Noise	$< 5\times10^{-20}$	$< 1\times10^{-17}$	<**TBR** 1.2×10^{-15}	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (40 Hz)
	$< 7\times10^{-21}$	$< 1.4\times10^{-18}$	<**TBR** 6×10^{-18}	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (100 Hz)

Thermal Noise Requirements

Thermal noise requirements

Mode	Average Effective Loss			*Freq.*
	TM	*BS*	*MCM*	
Internal Mode	$< 4\times10^{-7}$	$< 1.6\times10^{-4}$	$< 1.4\times10^{-4}$	100 Hz
Pendulum Mode	$< 3\times10^{-6}$	$< 1.2\times10^{-3}$	**TBD**	100 Hz

Seismic Noise Requirements

Seismic noise requirements

Component	Transfer Function of Suspended Component			Freq (Hz)
	TM	BS	MCM	
horizontal to horizontal	$< \left(\frac{0.74\text{Hz}}{f}\right)^2$	$<20\times \left(\frac{0.74\text{Hz}}{f}\right)^2$	$<2000\times \left(\frac{0.74\text{Hz}}{f}\right)^2$	10 - 100
vertical to horizontal	$<3\times10^{-4}$	$<1.2\times10^{-2}$	<1.2	10 - 100

Control Noise Requirements

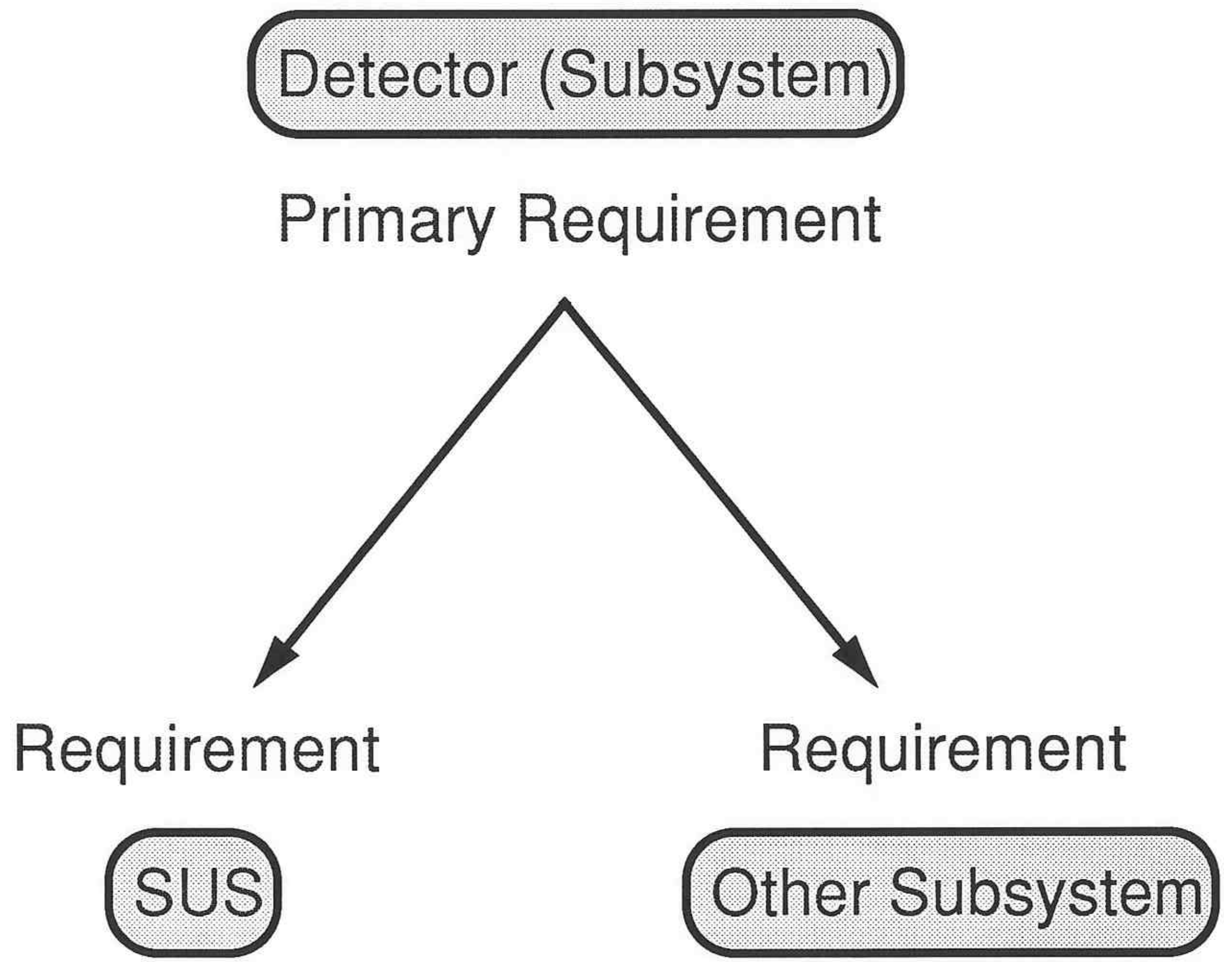
Control noise requirements

Noise per Mass	*Requirement*			*Unit (Freq.)*
	TM	*BS*	*MCM*	
Control Noise	$< 5\times10^{-20}$	$< 1\times10^{-17}$	$< 1.2\times10^{-15}$	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (40 Hz)
	$< 7\times10^{-21}$	$< 1.4\times10^{-18}$	$< 6\times10^{-18}$	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (100 Hz)

Scattered Light Effect Reduction

TBD

Performance Requirement Flowdown (I)



Performance Requirement Flowdown (II)

Performance requirement flowdown

Requirement Entry of SUS	*Other Subsystem*	*Requirement Entry of the Subsystem*	*Primary Requirement*
Longitudinal Motion Dynamic Range in Operation (TM, MCM)	Env.+ SEI + SUS	Longitudinal Motion of Component	No Saturation on Lock Holding (LSC)
	LSC	Residual RMS Longitudinal Motion of Component	
Longitudinal Motion Dynamic Range in Acquisition (TM, MCM)	Env. + SEI + SUS	Longitudinal Motion of Component	Capability of Lock Acquisition (LSC)
	LSC	Acquisition Method	

Performance Requirement Flowdown (III)

Performance requirement flowdown

Requirement Entry of SUS	*Other Subsystem*	*Requirement Entry of the Subsystem*	*Primary Requirement*
Orientation Dynamic Range (TM, BS, MCM)	Env. + SEI + SUS	Angular Motion of Component	No Saturation on Orientation Control (ASC)
	ASC	Residual RMS Angular Motion of Component	
Longitudinal Motion & Orien-tation Dynamic Range (All Components)	Env. + SEI	Longitudinal Motion of Optics Platform/ Stack Top Plate	No Saturation on Suspension's Control (SUS)
Loss of Internal Modes due to Attachments (TM, BS)	CO	Loss of Internal Mode for Blank Mass	Internal Mode Thermal Noise (Detector)

Performance Requirement Flowdown (IV)

Performance requirement flowdown

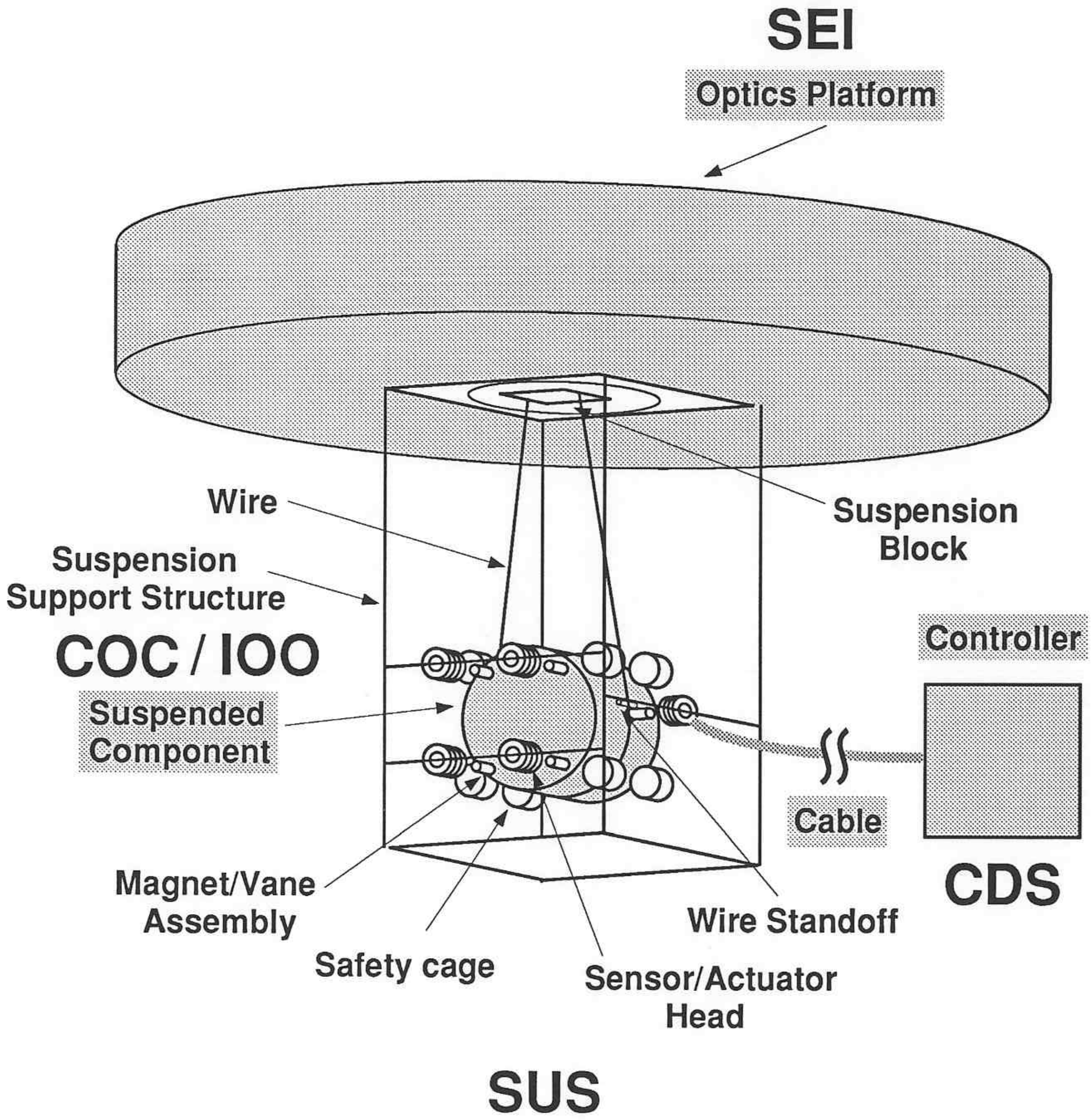
Requirement Entry of SUS	*Other Subsystem*	*Requirement Entry of the Subsystem*	*Primary Requirement*
Loss of Internal Modes due to Attachments (MCM)	IOO	Loss of Internal Mode for Blank Mass	Internal Mode Thermal Noise of MC Mirror (IOO)
Loss of Pendulum Modes (TM, BS)	N/A	N/A	Pendulum Mode Thermal Noise (Detector)
Loss of Pendulum Modes (MCM)	N/A	N/A	Pendulum Mode Thermal Noise of MC Mirror (IOO)
Transfer function of Pendulum (TM, BS)	Env. + SEI	Motion of Optics Platform	Seismic Noise (Detector)

Performance Requirement Flowdown (V)

Performance requirement flowdown

Requirement Entry of SUS	*Other Subsystem*	*Requirement Entry of the Subsystem*	*Primary Requirement*
Transfer function of Pendulum (MCM)	Envi. + SEI	Motion of Stack Top Plate	Seismic Noise of MCM (IOO)
Control Noise (TM, BS)	N/A	N/A	Non-Primary Noise (Detector)
Control Noise (MC Mirror)	N/A	N/A	Non-Primary Noise of MC Mirror (IOO)
Scattered Light Effect Reduction	Detector	Raw Scattered Light noise	Scattered Light Noise (Detector/IOO)

Mechanical Interfaces (I)

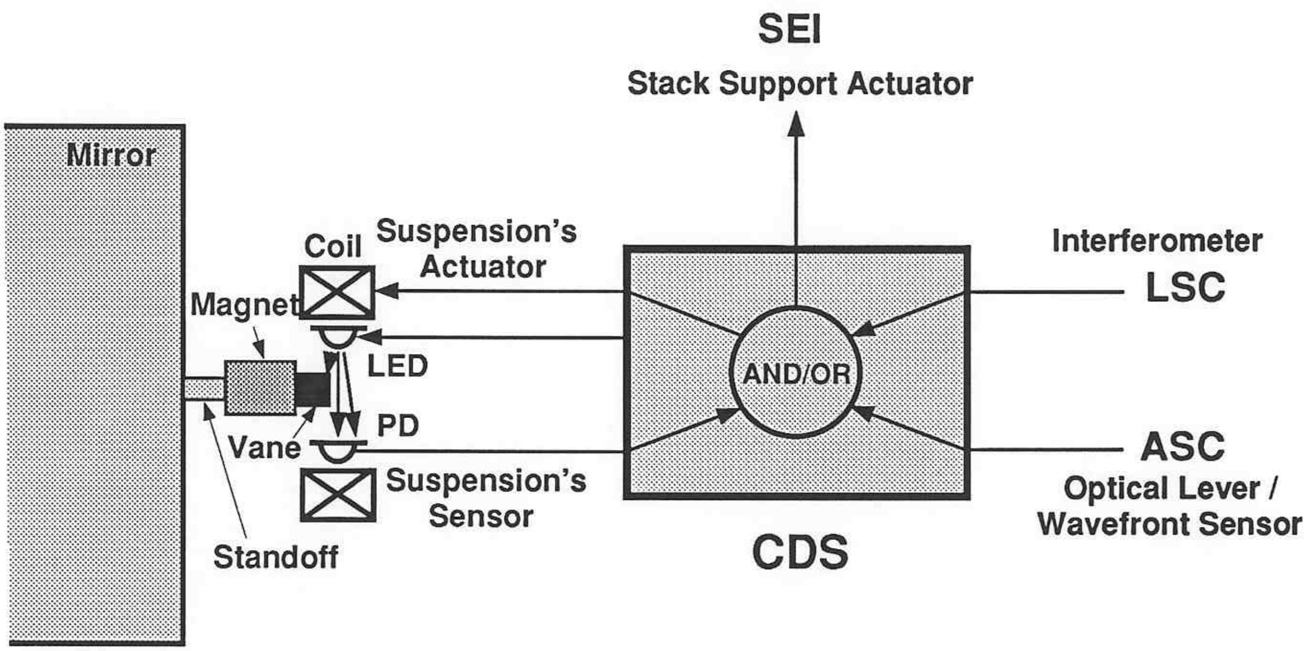


Mechanical Interfaces (II)

Mechanical interfaces between SUS and other subsystems

Other Subsystem	*SUS's Parts*	*Other Subsystem's Parts*
SEI	Top Plate of Support Structure	Optics Platform
SEI	Bottom Plate of Support Structure	Stack Top Plate
COC/IOO	Suspension Wire	Optical Component
COC/IOO	Wire Standoff	Component
COC/IOO	Magnet Standoff	Component
CDS	Sensor/Actuator Head	Connector/cable

Signal Interfaces



Signal Interfaces between SUS and other subsystem.

Other Subsystem	*Signal*	*Signal Flow SUS <--> Sub.*
LSC	Interferometer Signal	<--
ASC	Optlev Signal and/or Wavefront Signal	<--
SEI	Stack pushing Signal	?
IOO	Mode Cleaner Signal	<--

Features of Conceptual Design

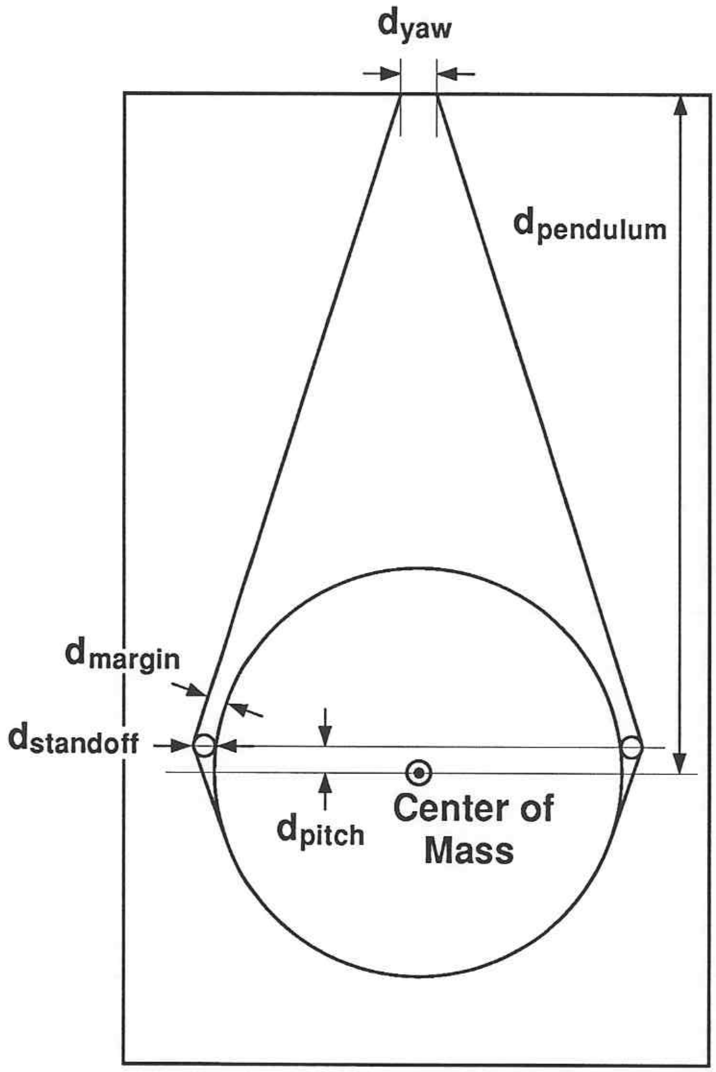
- The suspension assembly is held together by a suspension support structure.
- The optical component is suspended by a single loop of wire from a suspension block, using wire standoffs between the suspension wire and the component.
- The position and the orientation of the optical component are detected by five edge sensors, consisting of a magnet/vane assembly attached to the optical component and an LED/ photodiode pair.
- The optical component is to be damped or to be controlled by five magnet/coil actuators.
- The optical component is protected or held during transfer by a safety cage.

Suspension Support Structure

- The suspension assembly will have a modular support structure.
- The optical component is suspended from the suspension block, which is fixed to the top plate of the support structure.
- The sensor/actuator heads and the safety cage are also attached to the support structure.
- The support structure must have a function of changing coarsely its position and orientation.
- The suspension support structure need to be sufficiently rigid so that mechanical resonances do not shake the sensor/actuator head and put excess force on the suspended component.

Suspension Configuration

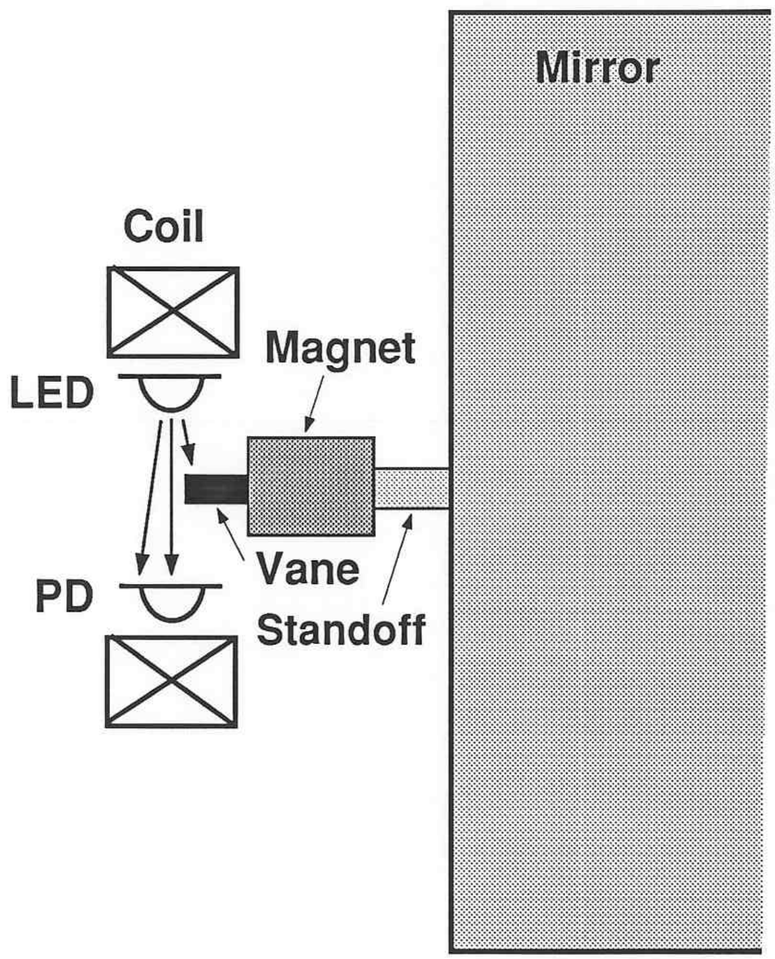
Suspension configuration (No Wedge)



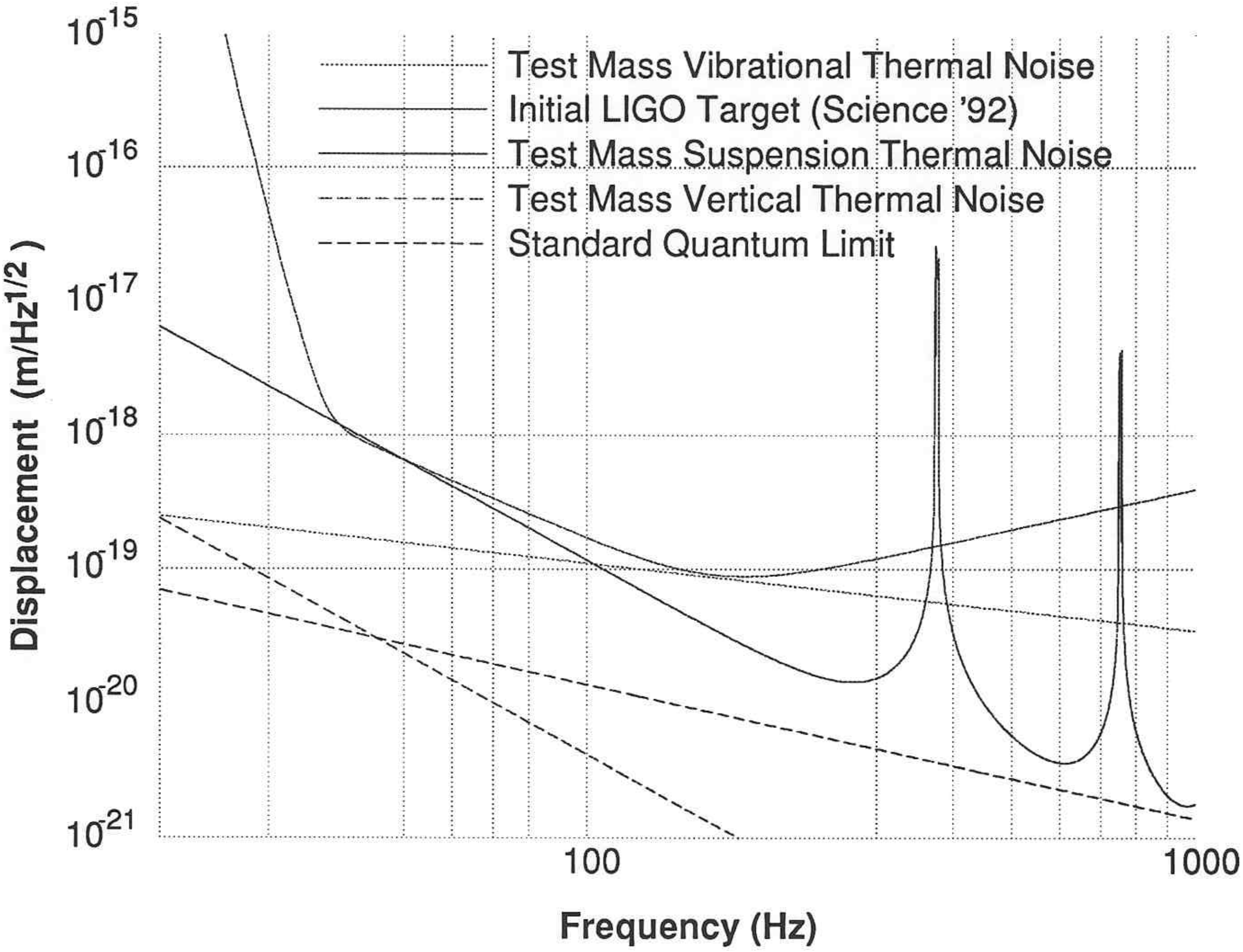
Physical Quantity	*Specification*		
	TM	*BS*	*MCM*
$f_{pend.}$ (Hz)	0.74	0.74	0.84
f_{pitch} (Hz)	0.5	0.5	**TBD**
f_{yaw} (Hz)	0.5	0.5	**TBD**
$d_{pend.}$ (cm)	45	45	35
d_{pitch} (mm)	5	6.5	**TBD**
d_{yaw} (mm)	34	39	**TBD**
$d_{standoff}$ (mm)	3.1	5.5	**TBD**
d_{margin} (mm)	0.5	0.5	**TBD**

Sensor/Actuator Head & Magnet/Standoff Assembly

- Edge sensor
- No active LED stabilization
- No preamplifier on Head
- No vane



Thermal Noise of Suspended Test Mass

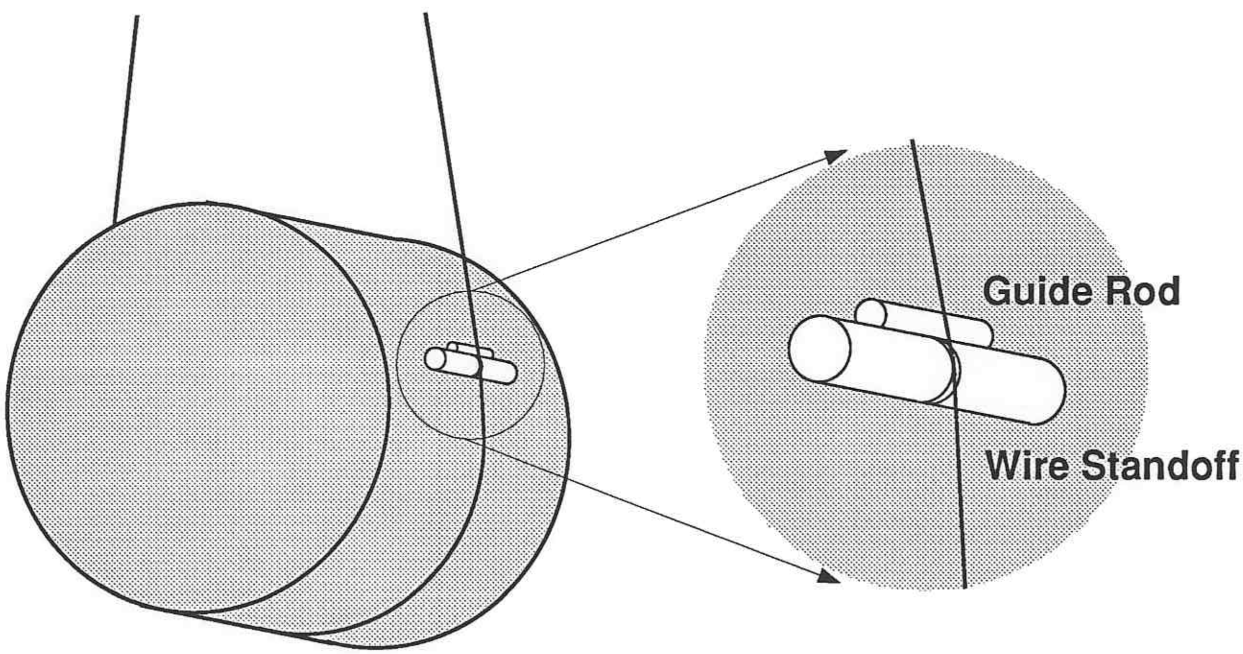


Control Noise and Dynamic Range

- The equivalent displacement noise of the sensor is $1\times10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$ above 40 Hz.
- The servo loop gain is 5×10^{-8} at 40 Hz, and 7×10^{-9} at 100 Hz.
- Crosscoupling from transverse to longitudinal force is 0.01
- (Finesse of the arm cavity is 100.)
- The efficiency of the suspension's actuator is 0.02 N/A above 40 Hz.
- The driver current noise including the Johnson noise is $1.5\times10^{-12}\mathrm{A}/\sqrt{\mathrm{Hz}}$ above 40 Hz.
- The maximum current below 0.15 Hz is 100 $\mathrm{mA_{pp}}$.

Grooved Wire Standoff

- Grooved quartz (?) rod
- Guide quartz rod



Safety Cage

TBD

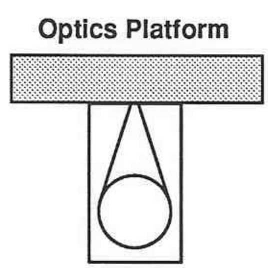
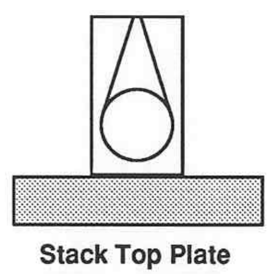
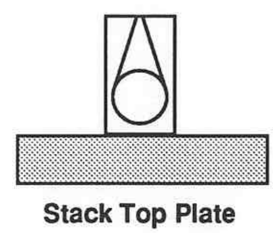
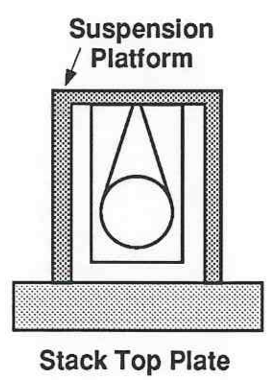
- The motion of the optical component is restrained to protect the component and the magnet/standoff assembly.
- The suspended component is held firmly during installation, transfer, and lifting.
- A manually adjustable cage will be used in all locations except for components mounted in TMC chambers, which require motorized cage adjustment in vacuo.
- Problem of electrostatic force will be considered.

Stray Light Shield

TBD

Suspension Assembly Installation

Suspension Assembly Installation

Suspen-sion Type	LOS 1/LOS 2 **TBD** (Common or different design ?)		SOS
Chamber Type	TMC/BSC	HAM	HAM
Installation			
Alternative Method	N/A		N/A

Check-out of Assembly/Test Fixtures

- Demonstrate gluing of magnet/standoff assemblies and guide rods onto aluminum model fixtures using special gluing fixtures

Fit Check and Constructability Verification

- Fit checks of all seven configurations must be carried out, using aluminum models.

Possible reconfigurations.

Configuration	*Suspension Type*	*Safety Cage Type*	*Installation Type*
1	LOS 1	Manual	Hung
2	LOS 1	Motorized	Hung
3	LOS 1	Manual	Sit or Platform
4	LOS 2	Manual	Hung
5	LOS 2	Motorized	Hung
6	LOS 2	Manual	Sit or Platform
7	SOS	Manual	Sit

Alignment Tests

The alignment test will be done only for the LOS 1 suspension and SOS suspension using Aluminum models <u>TBR</u>.

- optical components can be aligned and balanced to within tolerances prior to gluing down standoffs.
- Optical components can be dismounted and remounted into proper optical alignment, within design tolerances.
- Coarse optical alignment and all clearance adjustments can be performed on a bench.

Q Measurements

The following Q measurements will be done using the suspension development facility for a suspended test mass and a suspended MC mirror:

- Resonance Q's of suspension wire violin resonances for lowest three harmonics of both wires
- Substrate vibrational mode Q's for lowest five axisymmetric modes

Sensor/Actuator Head Tests

- Electrical tests of the sensor/actuator head will verify that functionality and sensitivity specifications are met.
- The coupling strength between the actuator coil and magnet will be measured.

Check-out of Sensor/Actuator Head Testing Procedure

A test fixture will be developed for automated testing of sensor heads and an automated testing procedure will be demonstrated.

Demonstration of Local Damping

It will be shown that critical damping can be achieved under suspension's control making use of the servo electronics for the 40m suspension. This will be done for a LOS 1 suspension and SOS suspension, using aluminum models.

Transfer Function Tests

The transfer function will be measured for a LOS 1 suspension and a SOS suspension, using aluminum models. The response of the system will be measured for DC and for AC inputs over the relevant range of frequencies to show that the specified forces and torques can be applied to suspended components and that the requirements on mechanical resonances of the system can be met.

Rigidity Test

Excitation and measurement of higher frequency mechanical resonances will be attempted to identify the resonance frequencies and Q's of these resonances.

Feedback from R&D

One set of the suspension system will be first installed in Mark II to test its performance. The result of the test will be fed back to the SUS design for the detector.

Implementation