LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T070061-02-D ADVANCED LIGO 08/14/07

AOS: Stray Light Control (SLC) Design Requirements

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1 Introduction

1.1 Purpose

The purpose of this document is to specify the requirements for the Stray Light Control (SLC) subsystem of Advanced LIGO, which is a component of the Auxiliary Optics System (AOS).

1.2 Scope

The scope of the Stray Light Control subsystem is to control (through a combination of light baffling, beam dumps and attenuators) scattered light and stray/ghost beams in the interferometer, such that phase noise due to this light is negligible. In addition, since the trajectory of ghost beams depends on the COC wedge angle design, the Stray Light Control subsystem will collaborate with the Systems group on the choice of COC wedge angles.

The Stray Light Control subsystem will provide optical baffling around the COC elements and any other optical elements within the vacuum housing in order to reduce glare within the IFO to acceptable levels.

The Stray Light Control subsystem will control the passage of scattered light, which is not in the IFO mode, into the recycling cavity volume.

The Stray Light Control subsystem will provide errant beam baffles to protect the suspended optics from stray light beams if necessary; except in the IO section, which is the responsibility of IO. The IO section is defined as the entire in-vacuum optical plant between HAM 2 and the IO Baffle on HAM3.

The Stray Light Control subsystem will not provide baffling for other parts of the IO optical train, nor for the PSL optical train, nor for the ISC detection optical train.

The Stray Light Control subsystem will provide an ETM telescope baffle to block the excess light transmitted through the ETM that exceeds the clear aperture of the ETM telescope.

2 General description

2.1 Stray Light Control Components

The SLC subsystem will include the following components:

- ***Beam Dumps:*** *absorb the light from ghost beams and pick-off (PO) beams that originate from the wedged AR surfaces of the core optics mirrors.*
- ***Arm Cavity Baffles:*** *absorb the small-angle, scattered light arising from the arm cavity mirrors; this is the light scattered from the arm cavity HR mirror surface that propagates 4km to the end of the beam tube, within the far beam tube aperture.*
- ***Elliptical Baffles:*** *absorb the excess light that spills around the clear aperture of the PRM and the tilted BS.*
- ***Manifold Baffles:*** *eliminate the reflection of the wide-angle diffuse scattered light from the arm cavity HR mirrors at the viewport spool-piece near the cryopump at the entrance to the arm.*
- ***Brewster Windows:*** *provide a vacuum barrier between HAM 1 and HAM 2, and between HAM 5 and HAM 6.*
- ***Cryopump Baffles:*** *obscure the reflecting surfaces of the cryopumps within the arm cavity near the input test mass mirrors.*
- ***IO Baffle:*** *reduce the passage of scattered light from the input (IO) optics region into the recycling cavity region.*
- ***Output Faraday Isolator:*** *attenuates light that is back-scattered into the mode of the interferometer from the output optical chain.*
- ***ETM Telescope Baffle****: absorbs the light transmitted by the ETM that is outside the aperture of the ETM beam reducing telescope.*

2.2 Ghost Beam Naming Convention

The ghost beam naming conventions for the COC mirrors and the beam splitter are shown in the following figures.

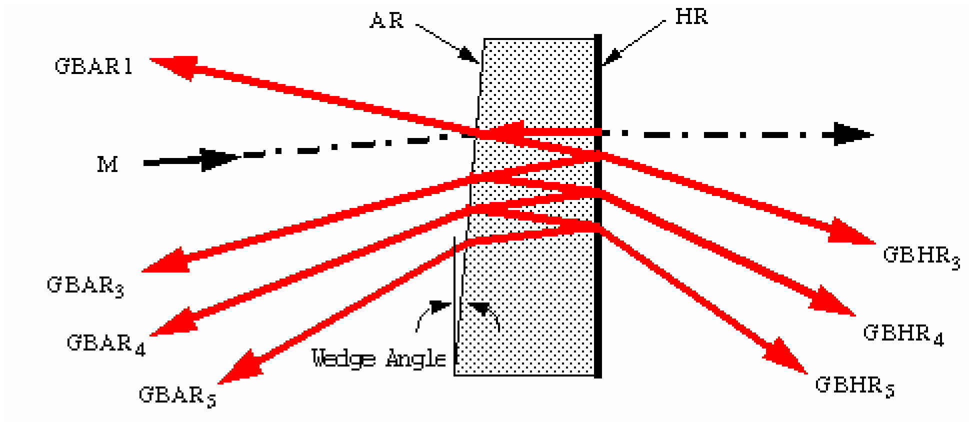

Figure 1: PRM, SRM, ITM, and ETM ghost beam naming convention

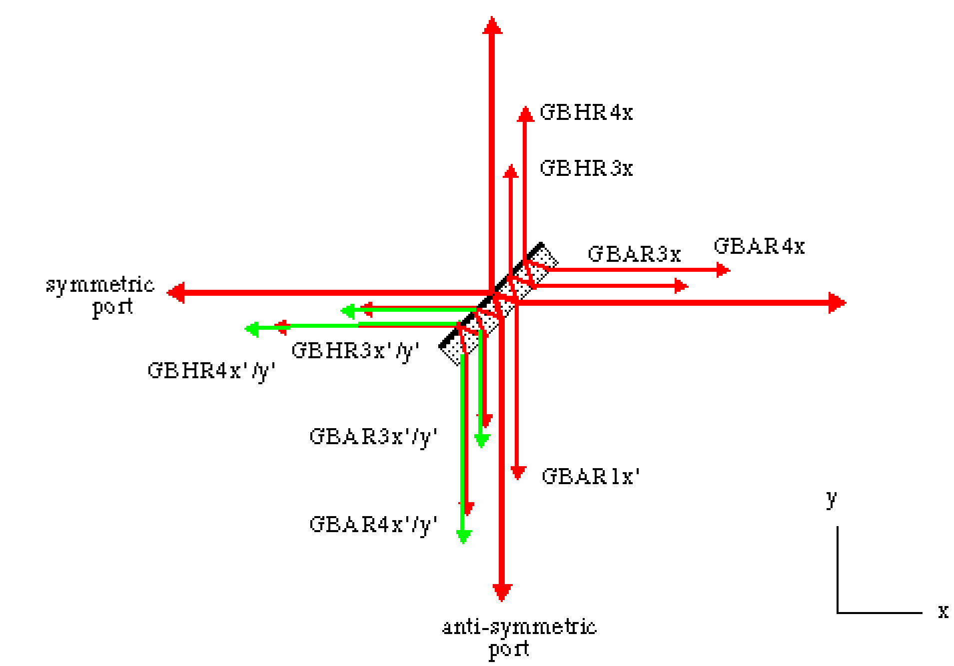

Figure 2: BS ghost beam naming convention

The GBAR3x'/y' are superimposed, and are renamed GBAR3P. Likewise, the other superimposed pairs are renamed GBAR4P, GBHR3P, GBAR4P.

3 Input to the Design Requirements

3.1 Interferometer Design Parameters

The following tables list the interferometer design parameters used for the scattered light analysis.

Table 1: COC Characteristics Assumed for Scattered Light Analysis

Physical Quantity	PRM	SRM	BS	CP	ITM	ETM
AR reflectivity @ 1064 nm	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Wedge angle, deg	0.08	0.08	1.67	0.83	1.45	0.167
HR reflectivity @ 1064 nm	0.79	0.96	0.5	0.0	0.995	0.99998
Refractive index @ 1064 nm	1.44963	1.44963	1.44963	1.44963	1.44963	1.44963
Recycling cavity elliptical beam radius, mm	107.1 H 122.5 V	107.1 H 122.5 V	107.1 H 122.5 V	107.1 H 122.5 V	107.1 H 122.5 V	
Arm cavity, 1ppm power contour radius, mm					158	158
beam radius parameter w, mm	60	60	60	60	60	60
Mirror diameter, mm	265	265	370	276	340	340
Clear aperture diameter, mm	245	245	350	256	320	320
Mirror thickness, mm	100	100	60	65	200	200

Table 2: Interferometer Design Parameters

ITEM	VALUE
Input laser power	125 W
Recycling cavity power gain	16.9
Arm cavity power gain	792
Recycling cavity power	2110 W
Arm cavity power	834000 W
IFO Gaussian beam waist radius, w	11.5 mm
Transmissivity of ETM HR	15 ppm
$\Delta\Omega_{IFO}$ (cavity mode solid angle)	2.72e-9 sr
ETM transmitted power	12.5 W
REFL power	0.125 W

ITEM	VALUE
AS power	0.135 W
Power incident on Arm Cavity Baffle	7.4 W
Power incident on Cryopump Baffle	2.8 W
Power incident on Elliptical Baffle from ITM	1.4 W

3.2 Vibration Environment

The motions of the various surfaces that were used to calculate the scattered light noise are described in the following.

3.2.1 Vacuum Enclosure Motion

SLC components may be attached to walls of the vacuum enclosure or light may scatter from the walls, and in such cases the vibration spectra shown in the figures below are used for scattered light calculations.

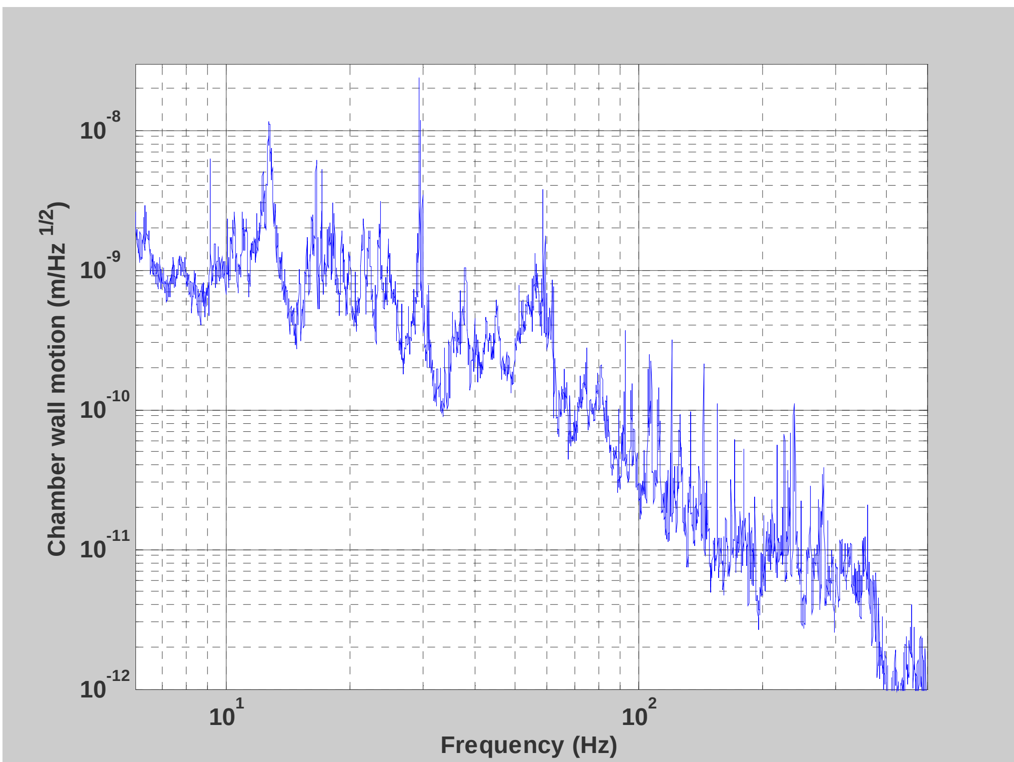

Figure 3. Motion spectrum of the LHO BSC7 chamber wall, measured with an accelerometer mounted at beam height; accelerometer axis is perpendicular to the wall. Measured by Robert Schofield, 17 November 2006 (see LHO iLog entry, 17 Nov 2006, 17:39:30 local).

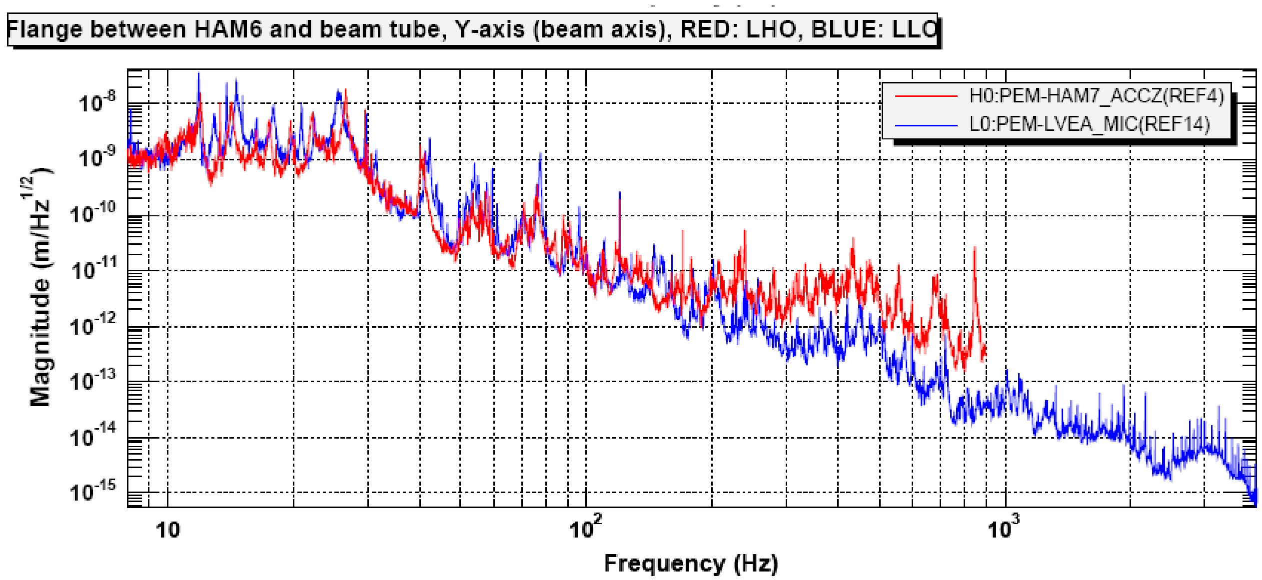

Figure 4. Motion spectra of the beamtube flange on HAM6 for both H1 (Nov 06) and L1 (March 07). Measurements made by R. Schofield, and are described in the LLO detector log, March 22, 2007.

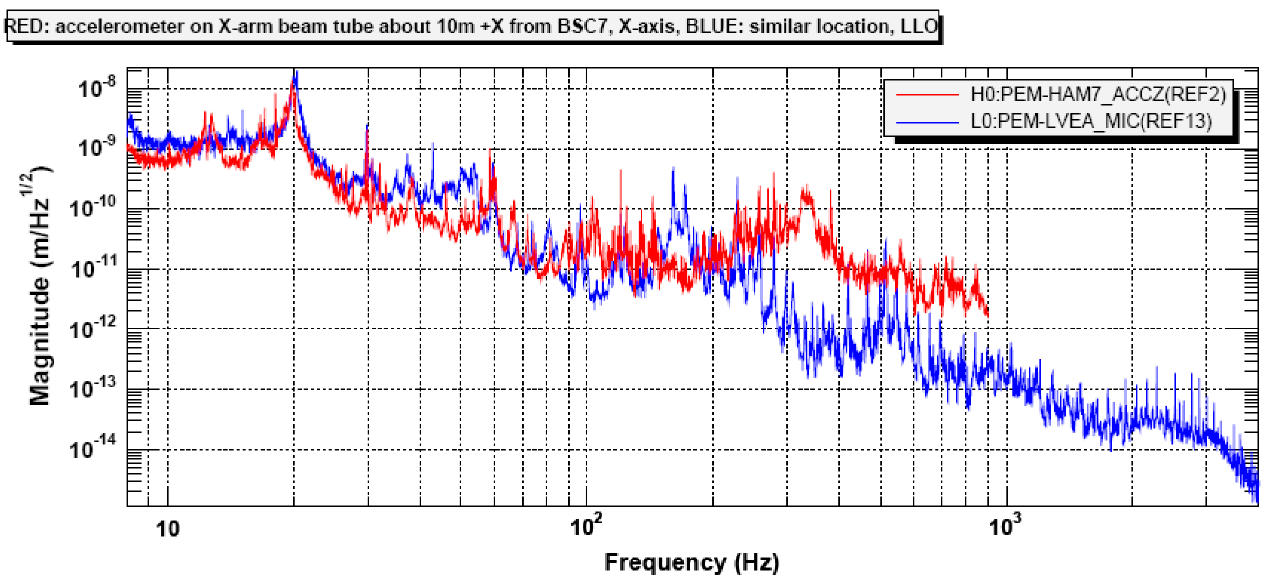

Figure 5. Motion spectra of the X-arm beam tube, along the x-axis, approximately 10 m from BSC7. Measurements made by R. Schofield, and are described in the LLO detector log, March 22, 2007.

3.2.2 BSC and HAM SEI Table Motion

The SLC components that are mounted to the BSC and HAM seismic platform motions will be assumed to have the displacement noise requirement levels found in *LIGO-E990303-03 Seismic Isolation Subsystem Design Requirements Document*, and *LIGO-M060062-00 HAM Single-stage Isolation Baseline Option Review Report*. For frequencies above 30 Hz, the platform motion amplitude spectral density is assumed to be flat, at the 30 Hz value. As shown in Figure 6.

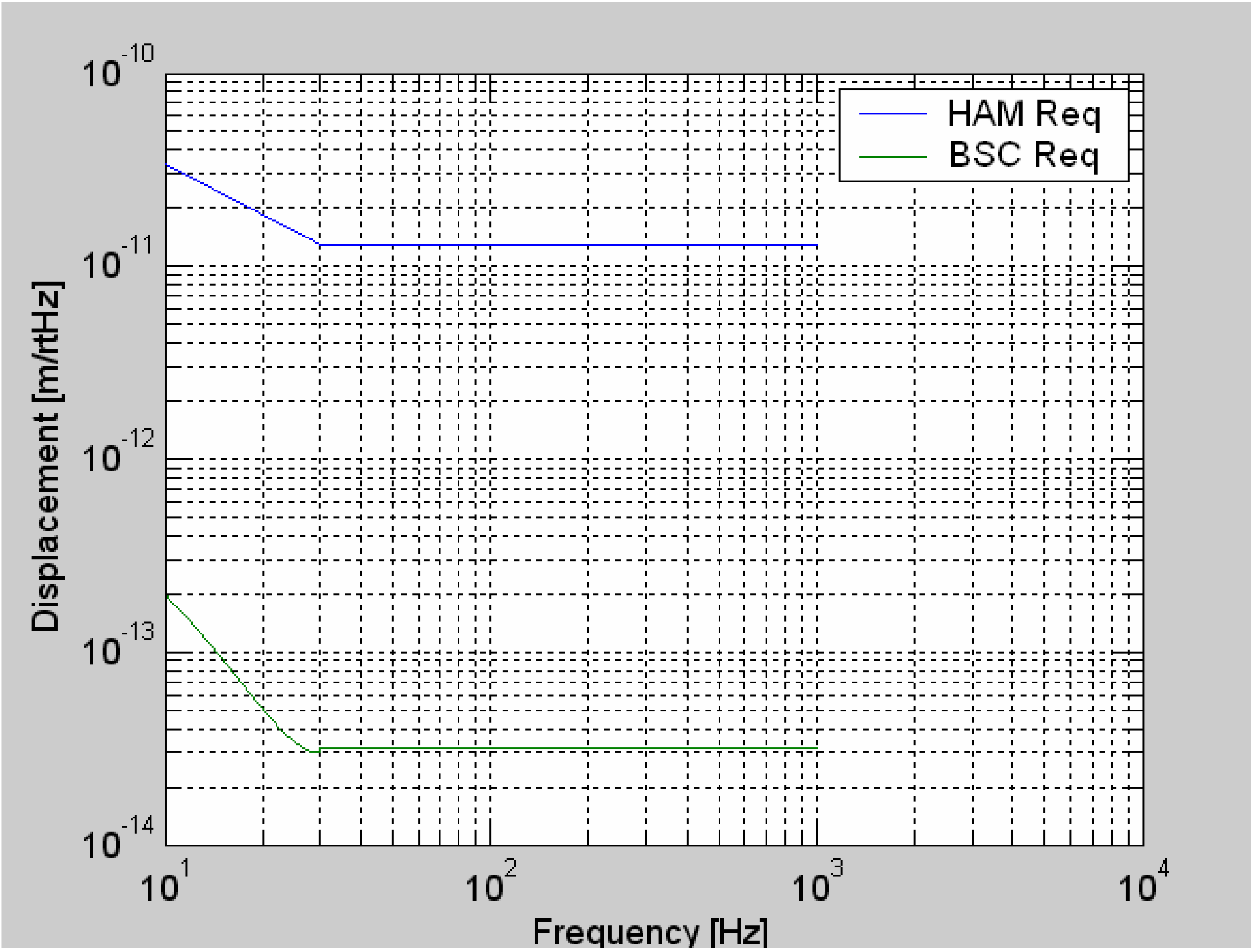

Figure 6: HAM and BSC SEI Requirements

Some of the SLC components will be mounted to the HEPI structure in the BSC chamber and will be assumed to have the x-displacement spectrum described by Brian Lantz, as shown in Figure 7. See **Error! Reference source not found.**.

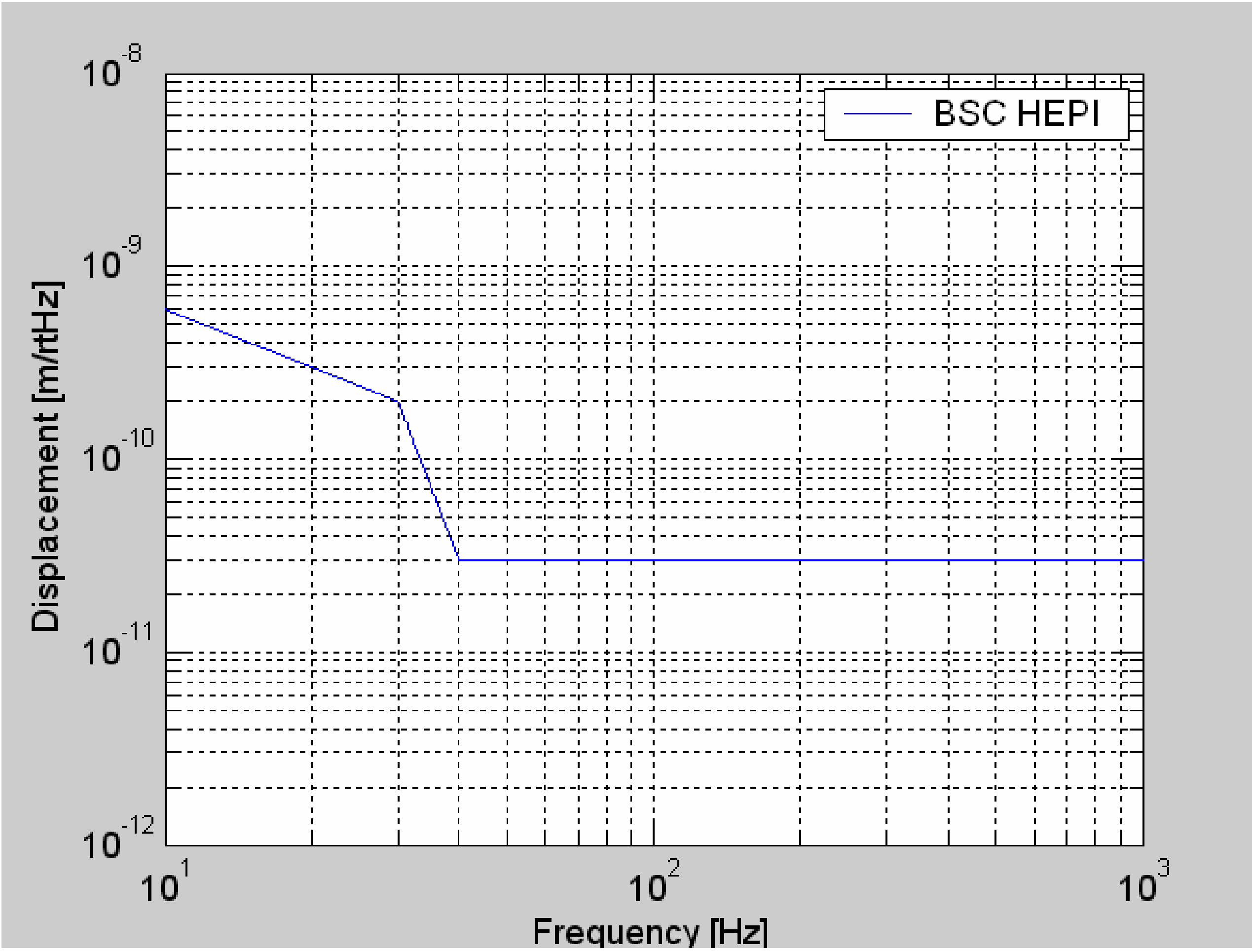

Figure 7: BSC HEPI Displacement Spectrum

3.3 Surface Scattering Values (BRDF)

Table 3: Assumed BRDF values.

PARAMETER	**VALUE**	**COMMENT**
$BRDF_{FI}$	5E-4 sr^-1	Ref. 18
R_{ACBAF}	0.01 sr^-1	estimate
$BRDF_{ACBAF}$	< 0.001 sr^-1	Estimate
$BRDF_{COC}$ ave to 3E-5 rad angle	1935sr^-1	Ref. 19
$BRDF_{VAC}$ @70 deg angle	0.025 sr^-1	Ref. 14
$BRDF_{Brew}$	5E-6 sr^-1	estimate

PARAMETER	VALUE	COMMENT
$BRDF_{BD}$	< 0.001 sr^-1	estimate
BRDF_ETM_Tel_Baffle	< 0.1 sr^-1	estimate
BRDF_cryopump_baffle	0.01 sr^-1	estimate

3.4 Beam Characteristics

Table 4: Effective Beam Waist, Incident on Scattering Surfaces

Scattering Surface	Beam Waist
ITM, ETM	11.4 mm
Output Faraday Isolator	3.8 mm

3.5 More Parameters

The IFO parameters that were used for the scattered light calculations are listed in Table 5.

Table 5: IFO parameter values used for scattered light calculation

PARAMETER	VALUE	UNIT
IFO_length	4000	m
IFO_beamwaist	11.5e-3	m
IFO_beam_waist_RC	60e-3	m
beam_radius_ITM	6.00e-2;	m
beam_waist_photodetector	5e-3	m
beam_radius_Faraday	2.1e-3	m
lambda	1.064e-6	m
IFO_diffraction_angle	2.95e-05	rad
IFO_solid_angle	2.72E-09	sr
laser_power	125	W
recycling_cavity_power_gain	16.852	
arm_cavity_power_gain	792	
reflected_port_power_ratio	0.29250	relative to input laser power
dark_port_signal_ratio	0.00108	relative to input laser power

PARAMETER	VALUE	UNIT
reflected_port_power_ratio	1e-3	relative to input laser power
ITM_transmissivity	0.005	
ITM_HR reflectivity	0.995	
ETM_transmissivity	1.500e-05	
ETM_Reflectivity	0.99998	
PRM_AR_reflectivity	0.0005	
PRM_HR_reflectivity	0.78849199	
PRM_transmissivity	0.21150801	
SRM_AR_reflectivity	0.0005	
SRM_HR_reflectivity	0.96	
SRM_transmissivity	0.04	
BS_HR reflectivity	0.5	
BS_AR reflectivity	3.00e-04	
ITM_AR reflectivity	3.00e-04	
reflectivity_manifold_baffle	2.50e-01	
reflectivity_arm_cav_baffle	.01	
reflectivity_cryopump_baffle	.01	
reflectivity_cavity_beam_dump	5.00e-03	
reflectivity_ellip_baffle	.001	
Reflectivity_Faraday_AR	0.0025	

4 Requirements

4.1 Introduction

When light scatters from baffles, beam dumps, optical elements, or from the vacuum enclosure walls that have horizontal motion and is injected into the IFO optical mode, the phase shift of the injected light field will cause an apparent DARM signal (scattered light noise). The magnitude of the scattered light noise depends upon the particular point in the IFO into which the light is injected; and for small phase angles, the phase noise is proportional to the rms amplitude of the horizontal displacement of the scattering surface and to the electric field amplitude of the scattered light injected into the IFO. Fringe wrapping will occur for large phase angles and will generate noise at odd harmonics of the fundamental motion frequency of the scattering surface.

The transfer functions for the scattered light noise were determined by Hiro Yamamoto (see LIGO-T060073-00 Transfer Functions of Injected Noise). His model assumed that surface motions were small compared to the IFO light wavelength and neglected the optical spring effect at lower frequencies. The transfer functions were calculated with an assumed RSE detuning of 0.06 radians, which causes a dip in the LIGO sensitivity at 250 Hz.

4.2 Noise Requirements

4.2.1 Direct Requirements

Phase noise due to scattered light fields injected into the interferometer is treated as a technical noise source. Therefore, the total scattered light phase noise, expressed in equivalent displacement noise, must be < $1/10^{th}$ of the quadrature sum of the suspension thermal noise and the test mass thermal noise (referred to as the SRD), as given in Figure 1 of M060056-06, Advanced LIGO Reference Design.

Sources of scattered light phase noise are divided into two categories: 1) those between the interferometer and the interface where AOS delivers beams to ISC for sensing, and 2) those within the ISC sensing chains. The preceding noise requirement applies to all the scattered light; we will apportion the allowed noise equally between SLC (AOS) and ISC. Therefore, since the scattered light phase adds in quadrature, the total scattered light phase from sources and paths within SLC/AOS must be < $1/14^{th}$ of the thermal noise envelope.

Furthermore, because there can be large uncertainties in the estimation of scattered light, additional margin—beyond the factor of 10—should be designed in where it is prudent and feasible.

4.2.2 Implied Requirements for Scattering Surfaces

The scattered light noise analysis will be used to derive implied requirements on the optical properties and vibration levels for each of the SLC components listed in 2.1.

4.3 Output Faraday Isolator Requirements

The Output Faraday Isolator shall transmit > 95% optical power in the forward direction. The power isolation factor of the Faraday shall be 30 dB minimum in the reverse direction.

4.4 IO Baffle Requirements

All scattered light on HAM1, HAM2, and HAM3 that does not scatter into the mode of the IFO shall be blocked from entering the recycling cavity section of the IFO.

4.5 Cryopump Baffle Requirements

The Cryopump Baffles shall block scattered light from the HR surfaces of the ITM and ETM from impinging on the surfaces of the cryopumps in the arm cavity. They shall fit within the same space allocated to the Cryopump Baffles for Initial LIGO.

4.6 BSC Chamber Components

Any SLC components mounted in BSC chambers (elliptical baffles, arm cavity baffles, cavity beam dumps) shall not interfere with nor compromise the performance of any Suspensions in those chambers.

4.7 Clear Aperture Requirements

Component	*Clear Aperture*
Arm cavity baffles	Shall not vignette the clear aperture of the ITM and ETM mirrors
Elliptical baffles	Shall be larger on all sides than the limiting aperture that is determined by the geometric shadow of the PRM and the BS
Cavity beam dumps	Shall not vignette the recycling cavity beam > 100 ppm power loss; Shall not vignette the arm cavity beam > 1 ppm
Cryopump baffles	Vignetting of the main beam by the cryopump baffles shall not significantly increase the power loss in the arm cavity
IO baffle	CA shall be 6 mm larger than the CA diameter of the PRM
Output Faraday Isolator	Minimum CA shall be > 1 ppm diameter of the beam passing through
ETM Telescope baffles	Shall not vignette the clear aperture of the ETM telescope

4.8 Generic Requirements

The SLC design shall conform to the generic detector subsystem requirements given in E010613, *Generic Requirements & Standards for Detector Subsystems.* These requirements are listed below.

4.8.1 Mechanical Characteristics & Standards

4.8.1.1 Stray Light Control Workmanship

All SLC components shall be manufactured according to good commercial practice.

4.8.1.2 Component Naming

All components shall be identified using the LIGO Naming Convention (LIGO-E950111-A-E).

4.8.2 Electrical Characteristics & Standards

Electrical equipment associated with the subsystem shall meet the EMI and EMC requirements of VDE 0871 Class A or equivalent. The subsystem shall also comply with the LIGO EMI Control Plan and Procedures (LIGO-E960036).

4.8.3 Vacuum Compatibility Requirements

All materials used inside the vacuum chamber shall comply with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D).

4.8.3.1 Materials and Processes

The materials and processes used in the fabrication of the Stray Light Control subsystem shall be compatible with the LIGO approved materials list, LIGO Vacuum Compatible Materials List (LIGO-E960022).

Metal components shall have appropriate protective finishes on all surfaces, suitable for vacuum installation.

4.8.3.1.1 Processes

4.8.3.1.1.1 Cleaning

All materials used inside the vacuum chambers shall be cleaned in accordance LIGO-E960022-00-D or LIGO-E000007-00, and Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D).

4.8.4 Acoustic Requirements

SLC equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. As a minimum, equipment shall not produce acoustic noise levels greater than specified in Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083.

4.8.5 Earthquake Requirements

The suspended SLC assemblies and the assemblies mounted to the vacuum chambers shall withstand normal ground seismic disturbances.

Earthquake stops and/or other provisions shall be provided so as to minimize catastrophic damage to the SLC equipment.

4.8.6 Operating Environment

The SLC assemblies shall be designed to operate in the high vacuum environment of the IFO and in the LVEA environment during installation.

4.8.7 Quality Assurance

4.8.7.1 General

4.8.7.1.1 Responsibility for Tests

AOS shall conduct tests to verify the as-delivered performance specifications of the sub-system.

4.8.7.1.2 Special Tests

4.8.7.1.2.1 Engineering Tests

TBD

4.8.7.1.2.2 Reliability Testing

TBD

4.8.7.1.3 Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan (LIGO-M050220-02, Guidelines for Advanced LIGO Detector Construction Activities).

4.8.7.2 Quality conformance inspections

4.8.7.2.1 Inspections

Manufactured parts with LIGO identification numbers or marks shall be inspected to determine conformity with the procurement specification.

Witness samples will be acceptable proof of the properties of HR and AR coatings applied to the optical surfaces.

4.8.7.2.2 Demonstration

The required attenuation characteristics of the assembled Faraday isolator shall be demonstrated prior to installation.

The required mechanical characteristics of the suspended assemblies shall be demonstrated before installation.

4.8.7.2.3 Test

Appropriate tests shall be implemented to verify the specifications of the purchased components.

4.8.8 Reliability

SLC assemblies shall operate reliably and shall not substantially impact the operating duty cycle of the IFO.

4.8.9 Maintainability

Passive SLC assemblies shall require no maintenance during normal operation of the IFO. In the event of catastrophic damage, passive SLC assemblies shall be repaired by replacement of subassemblies or parts that constitute the subassemblies.

Active SLC assemblies, such as the PO Mirror suspensions and the Faraday Isolator suspensions, shall be repaired by replacement at the board level with a minimum down-time of the IFO.

4.8.10 Documentation

The documentation shall consist of working drawings, assembly drawings, and alignment procedures for the SLC assemblies.

4.8.10.1 Custom Specifications

Manufacturing specifications for custom SLC components and assemblies shall be developed.

4.8.10.2 Design Documents

The following documents shall be produced:

- Conceptual Design Document (including supporting technical design and analysis documentation)
- Preliminary Design Document (including supporting technical design and analysis documentation)
- Final Design Document (including supporting technical design and analysis documentation)
- Installation Procedures

4.8.10.3 Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication shall be provided along with Bill of Material (BOM) and drawing tree lists. The drawings shall comply with LIGO standard formats and shall be provided in electronic format. All documents shall use the LIGO drawing numbering system, LIGO-E030350-A, Drawing Requirements.

4.8.10.4 Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering scheme, LIGO-E030350-A, Drawing Requirements

4.8.10.5 Test Plans and Procedures

A test plan shall be developed for verifying the specifications of the purchased components, in accordance with LIGO M050220-02, Guidelines for Advanced LIGO Detector Construction Activities.

4.8.11 Transportability

All SLC assemblies shall be transportable by commercial carrier without degradation in performance.

4.8.11.1 Preparation

- Vacuum preparation procedures as outlined in LIGO-E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts.

4.8.11.2 Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage. Passive shock witness gauges shall accompany the crates of damage-susceptible assemblies during all transits.

4.8.11.3 Marking

Appropriate markings shall be provided for identification, delivery and storage, and to comply with regulations, statutes, and safety.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified in order to maintain a complete history of the component (in association with Documentation "travelers").

4.8.12 Safety

All components shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

Appendix A Acronyms

AOS - Auxiliary Optics System

AR - Antireflection mirror coating

BRDF – bi-directional reflection distribution function

BS - Beam Splitter

BSC - Beam Splitter Chamber

CA – clear aperture

CDS – computer data systems

COC – core optics component

CP – compensation plate

DARM – differential arm

dB - decibel

Deg – degree

ETMx, ETMy - End Test Mass in the interferometer ‘X’ or ‘Y’ arm

GB – ghost beam

H – horizontal

HAM - Horizontal Access Module

HEPI - horizontal

HEPI – hydraulic external pre-isolation

HR – Hi-reflectance mirror coating

IFO - LIGO interferometer

IO - Input Optics

ISC- Interferometer Sensing and Control

ITMx, ITMy - Input Test Mass in the interferometer ‘X’ or ‘Y’ arm

LHO – LIGO Hanford Observatory

LIGO - Laser Interferometer Gravitational-Wave Observatory

LLO – LIGO Livingston Observatory

m/rtHz – meter per square root Hertz

mm – millimeter

nm – nanometer

PO - Pick-off

ppm - parts per million

PRM – Power Recycling Mirror

PSL – pre-stabilized laser

R - reflectivity

SEI - seismic

SLC – Stray Light Control

sr - steradian

SRD - Science Requirements Document

SRM – Signal Recycling Mirror

V - vertical

w – Gaussian beam radius parameter

W – Watt

Appendix B Applicable Documents

1. LIGO-E010613 Generic Requirements & Standards for Detector Subsystems
2. LIGO-E030350-A, Drawing Requirements
3. LIGO-E950111-A LIGO Naming Convention
4. LIGO-E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
5. LIGO-E960036 LIGO EMI Control Plan & Procedures
6. LIGO-E990303-03 Seismic Isolation Subsystem Design Requirements Document
7. LIGO-L970061-00-D Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation
8. LIGO-M050220-02, Guidelines for Advanced LIGO Detector Construction Activities
9. LIGO-M060056-06 Advanced LIGO Reference Design
10. LIGO-M060062-00 HAM Single-stage Isolation Baseline Option Review Report
11. LIGO-M950046-F LIGO Project System Safety Management Plan
12. LIGO-T060073-00 Transfer Functions of Injected Noise
13. LIGO-T960083 Derivation of CDS Rack Acoustic Noise Specifications
14. Rai Weiss, BRDF data, 9/20/95
15. Robert Schofield (11/17/06 LHO ILOG)
16. Robert Schofield (3/22/07 LLO ILOG)
17. SEI elog ID: 596 3/14/06, Brian Lantz
18. T920004-00 Estimation of Special Optical Properties of a Triangular Ring Cavity
19. T980027-00, Baffling Requirements for the 4K and 2K IFO