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- LIGO -
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Core Optics Support

Design Requirements Document

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1 INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the design requirements for the Core Optics Support (COS) subsystem. Primary requirements are derived ("flowed down") from the LIGO principal science requirements. Secondary requirements, which govern Detector performance through interactions between COS and other Detector subsystems, have been allocated by Detector Systems Engineering (see Figure 1.)

1.2. Scope

The COS subsystem generates optical pick-off (PO) beams from core optical elements and delivers those beams in an appropriate format outside the vacuum housing for use by the LSC/ASC in the feedback control of the interferometer (IFO) alignment and length, and for monitoring purposes. These PO beams comprise: RM PO, ITMx PO, ITMy PO, ETMx transmitted beams, and ETMy transmitted beams, SPS beam, APS beam, and the IFO control beam from the IOO. The COS will deliver the output beam from the dark (antisymmetric) port of the IFO. The COS subsystem will control or reduce to acceptable levels the intensities of all ghost beams (reflections from anti-reflection (AR) coatings and optic wedges) produced by COC. The COS subsystem also 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 COS does not include the optical pick-off of beams within the IOO or PSL subsystems. However, the COS will provide baffling at the output of the IOO telescope and a beam dump for the specular reflection from the SPS output window.

1.3. Definitions and Acronyms

- LIGO - Laser Interferometer Gravity Wave Observatory
- COS - Core Optics Support
- IOO - Input Optics
- DRD - Design Requirements Document
- SRD - Science Requirements Document
- RM - Recycling Mirror
- BS - Beam Splitter
- ITMx, ITMy - Input Test Mass in the interferometer 'X' or 'Y' arm
- ETMx, ETMy - End Test Mass in the interferometer 'X' or 'Y' arm
- AR - Antireflection Coating
- HR - Reflective mirror coating
- GBAR - Ghost Beam from AR side of COC
- GBHR - Ghost Beam from HR side of COC
- PO - Pick-off Beam
- vh - Vacuum housing
- SEI - Seismic Isolation subsystem

- SUS - Suspension subsystem
- ppm - parts per million
- ISC- Interferometer Sensing and Control
- LSC - Length Sensing and Control
- COC - Core Optics Components
- ASC - Alignment Sensing and Control
- IFO - LIGO interferometer
- HAM - Horizontal Access Module
- BSC - Beam Splitter Chamber
- BRDF - Bidirectional Reflectance Distribution Function
- TBD - To Be Determined
- APS - anti-symmetric port signal
- SPS - symmetric port signal
- rms - root-mean-square
- p-v, peak to valley

1.4. Applicable Documents

Table 1: LIGO Documents

Title/ Document Number
LIGO Science Requirements Document, LIGO-E950018-02-E
Detector Subsystems Requirements, LIGO-E960112-05-D
Secondary Light Noise Sources in LIGO, LIGO-T970074-00-D
Light Scattering and Proposed Baffle Configuration for the LIGO LIGO-GRP-200
Basis of the Optical Wavefront Specifications, LIGO-T952009-00-R
Note on Scattering in the Interferometer, Rai Weiss: see file pointer below
Motion of Optical Platforms Driven by Thermal Noise from Spring Elements, LIGO-T970055-00-D
Input Output Optics, DRD LIGO-T960093-01-D
Alignment Sensing/Control Design Requirements Document, LIGO-T952007-04-I
Alignment Sensing/Control Preliminary Design, LIGO-T970060-00-D
ASC Optical Lever Design Requirement Document, LIGO-T950106-01-D
Core Optics Components, DRD LIGO-E950099-03-D
End Test Mass Substrate, Dwg. D960791-A-D
Pre-stabilized Laser, DRD LIGO-T950030-02-D

Table 1: LIGO Documents

Title/ Document Number
LIGO Vacuum Compatibility, Cleaning Methods and Procedures, LIGO-E960022-00-D
Vacuum Equipment Specification, LIGO-E940002-02-V
HAM Assembly, LIGO Vacuum Equipment Dwg. V049-4-002
BSC, LIGO Vacuum Equipment Dwg. V0494-001
BSC End Cover, Type A11, LIGO Vacuum Equipment, Dwg. V049-4-A11
Core Optics Support Conceptual Design, LIGO-T970072-00-D
Seismic Isolation DRD, LIGO-T960065-02-D
Locally Damped Test Mass Motion, LIGO-T970092-00-D
Determination of the Wedge Angles for the Core Optics Components, T970091-00-D
Effect of PO Telescope Aberrations on Wavefront Sensor Performance, LIGO-T980007-00-D
COS Preliminary Design, LIGO-T980010-00-D

Note: Supporting documents which were used for calculations in the COS DRD can be found in the following files:

1)Determination of the Wedge Angles for Core Optics Components: /home/jaguar4/detector/systems/T970091-00.ps

2) Note on Scattering in the Interferometer: ~jordan/cos/T970083-00-D.fm

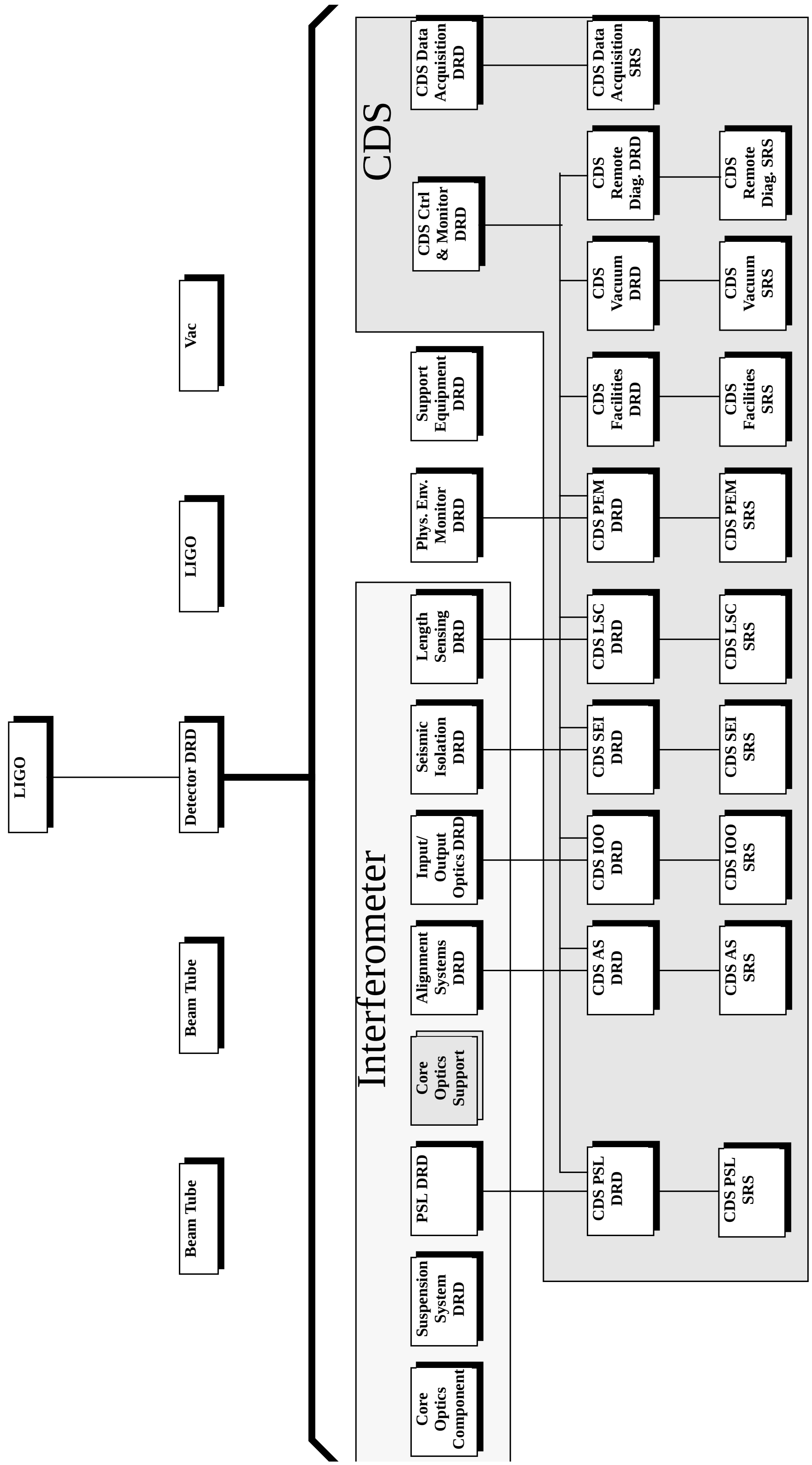
3) Secondary Light Noise Sources in LIGO: ~jordan/cos/T970074-00-D.fm(.ps)

4) Scattered Light and its Control in the LIGO Beam Tubes, Albert Lazzarini, LIGO Science Meeting Talk, 4/1/97

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is highlighted in the following figure.


LIGO
Detector DRD
Vac
LIGO
Beam Tube
Beam Tube
CDS
Interferometer
CDS Data Acquisition DRD
CDS Data Acquisition SRS
CDS Ctrl & Monitor DRD
CDS Remote Diag. DRD
CDS Remote Diag. SRS
CDS Vacuum DRD
CDS Vacuum SRS
Support Equipment DRD
CDS Facilities DRD
CDS Facilities SRS
Phys. Env. Monitor DRD
CDS PEM DRD
CDS PEM SRS
Length Sensing DRD
CDS LSC DRD
CDS LSC SRS
Seismic Isolation DRD
CDS SEI DRD
CDS SEI SRS
Input/ Output Optics DRD
CDS IOO DRD
CDS IOO SRS
Alignment Systems DRD
CDS AS DRD
CDS AS SRS
Core Optics Support
PSL DRD
CDS PSL DRD
CDS PSL SRS
Suspension System DRD
Core Optics Component

2.2. Product Perspective

The COS subsystem will provide optical pick-off beams for feedback control of the IFO, output signal beam from the dark port of the IFO, and will deliver those beams in an appropriate form outside the vacuum enclosure. COS will specify the wedge angles on the substrates of the recycling mirror (RM), the beam splitter (BS), the input test mass mirrors (ITMx and ITMy), and the end test mass mirrors (ETMx and ETMy). It will provide for the design and specification of beam reducing telescopes, turning mirrors, and optical windows so as to deliver the pick-off beams and signal beam through the optical ports in the vacuum chamber to a specified location with a specified beam waist.

The COS subsystem will control or reduce to acceptable levels the energy of the reflected ghost beams from the COC. This will be accomplished by designing absorbent baffling and housing elements to intercept and dissipate the energy of the spurious ghost beams.

The COS subsystem will provide baffling shrouds to control the scattered light from the COC into the arm cavity from re-entering the IFO.

A schematic layout of the detector assembly is shown in the figure following, indicating the physical relationship of the COS subsystem components to the rest of the detector system.

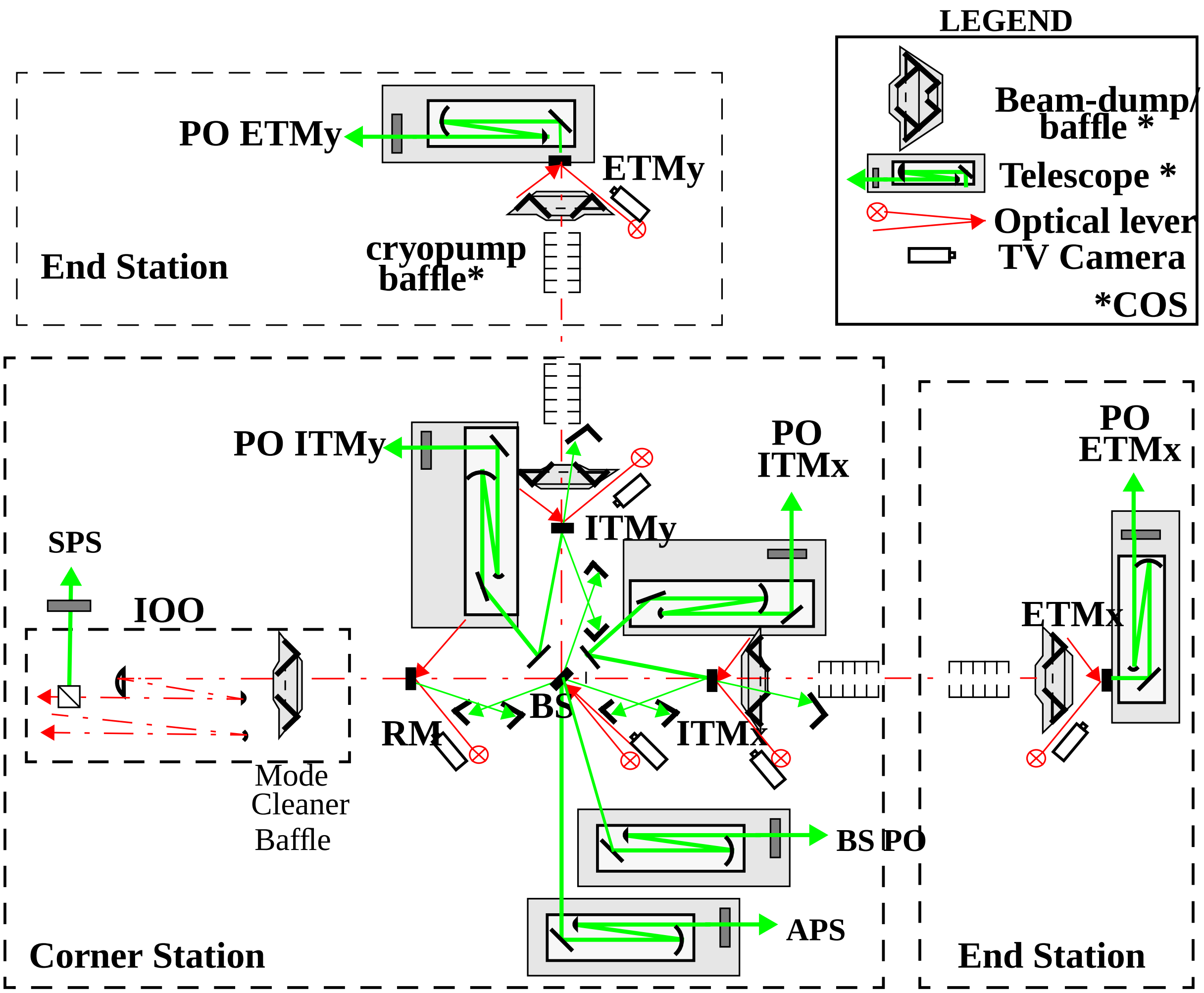


Figure 1: Core Optics Support Subsystem Elements, 4K IFO- Schematic Layout

2.2.1. Ghost Beam Designation

The ghost beams created by the wedge surface of the COC are designated according to the table, as shown in the schematic.

Table 2: Designation Optical Beams

Beam	*Designation*
pick-off	PO
ghost on AR side	$GBAR_n$, n=1...
ghost on HR side	$GBHR_n$, n=1...

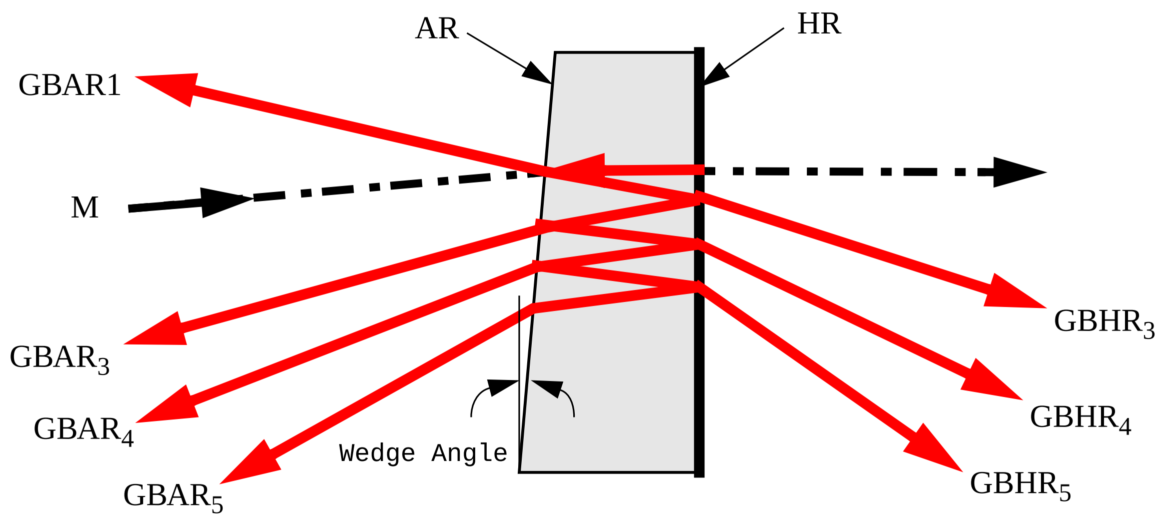


Figure 2: Optical Beam Designation: RM, ITM, ETM

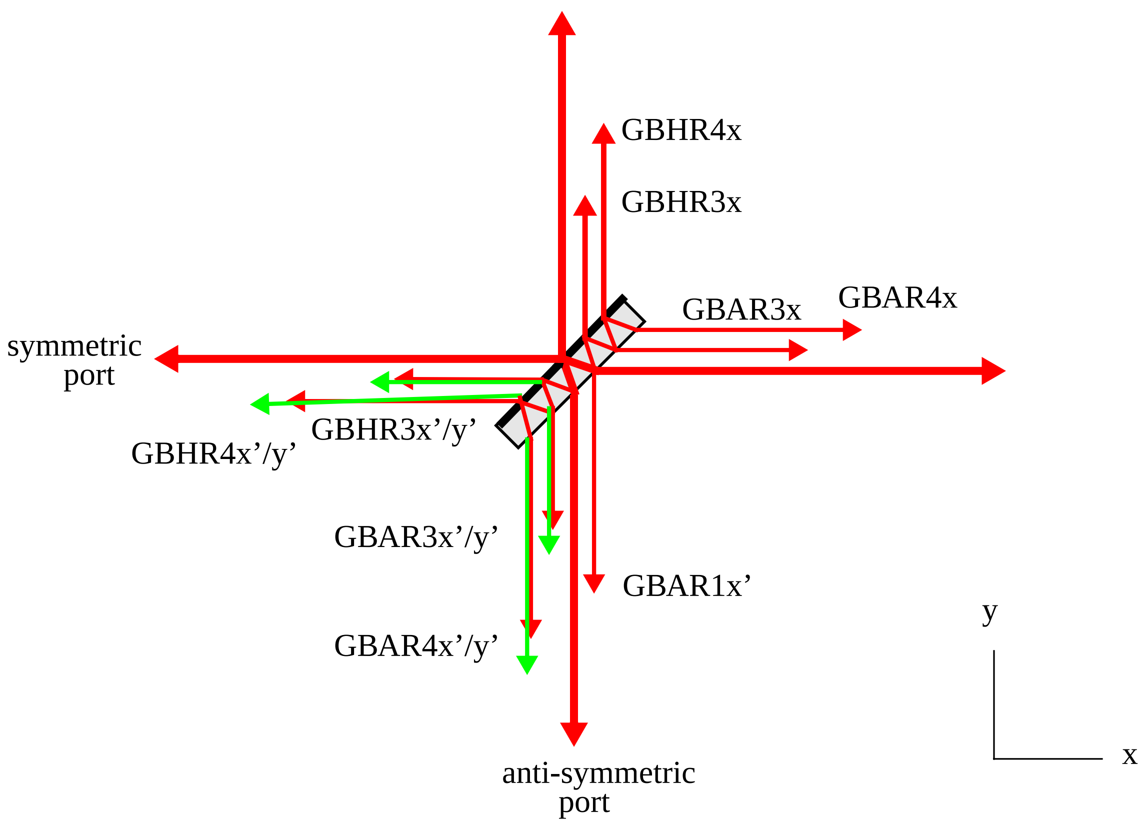


Figure 3: Optical Beam Designation: beam splitter

2.2.2. Optical Pick-off Beams for IFO Feedback Control, Initial Alignment, and Gravity Wave Sensing

The first internal reflection from the AR surface of the BS, both ITM mirrors, both ETM output beams, and the APS beam will be delivered outside the vacuum housing to the ISC.

2.2.3. COC Ghost Beam Control

The significant ghost beams (shown in Figure 2 as $GBAR_n$ and $GBHR_n$) from the COC will be captured and dissipated within beam-dump apparati.

2.2.4. Diffuse Scattered Light Control

The light scattered from any IOO and COC optical surfaces within the vacuum housing, which can adversely affect the interferometer performance, will be captured and dissipated within a beam baffle.

2.2.5. Delivery Optics for PO Beams, and APS Beam

Beam Reducing Telescopes and turning mirrors will be provided to reduce the size of the COC PO beams and the APS beam, and to direct these beams through the optical windows of the vacuum housings to the ISC subsystem.

2.3. General Constraints

2.4. Assumptions and Dependencies

2.4.1. Core Optics Parameters

See Core Optics Components DRD: LIGO-E950099-03-D

Table 3: Core Optics Parameters

Physical Quantity	*RM*	*BS*	*ITMx*	*ITMy*	*ETM*
AR coating @ 1060 nm	<0.001	<0.001	<0.001	<0.001	<0.001
AR coating @670 nm	>0.1	>0.1	>0.1	>0.1	NA
substrate thickness, cm	10	4	10	10	10
mirror reflectivity @ 1060 nm	.97	.5	.97	.97	.99998
mirror reflectivity @ 670 nm	>0.1	>0.1	>0.1	>0.1	>0.1
refractive index @ 1.06	1.45	1.45	1.45	1.45	1.45
100ppm power contour radius, cm	7.8	7.8	7.8	7.8	9.8

Physical Quantity	*RM*	*BS*	*ITMx*	*ITMy*	*ETM*
1ppm power contour radius, cm	9.6	9.6	9.6	9.6	12.0
beam radius parameter w, cm	3.64	3.64	3.63	3.63	4.57

2.4.2. ISC Interface Characteristics

2.4.2.1 ISC Sensor Beam Parameters

The COS pick-off beam characteristics will be compatible with the ISC design. See Alignment Sensing/Control Preliminary Design, LIGO-T970060-00-D

Table 4: PO Beam Parameters Delivered to ASC, COS Interface Requirements

Physical Quantity	*Characteristic*
PO beam aperture: RM, ITM	> 7.8 mm
PO beam aperture: ETM	>7.8 mm
wave front distortion	< 0.7λ p-v, See "PO Beam Optical Train Wavefront Distortion Requirement" on page 30.
beam waist position	to lie approx. 2m beyond vacuum chamber beam port
Gaussian beam radius parameter	w = 3.6 mm
beam height	within +/- 5cm of nominal IFO beam height
beam orientation	nominally horizontal, and above the surface of the ISC optics table
beam polarization	vertical (TBD)

2.4.3. Seismic Environment

The scattered light noise calculations in this document are based on the assumption that the rms velocity of scattering surfaces is sufficiently low so that upconversion of large amplitude low frequency motion does not produce in-band phase noise. This is true for the vacuum housing and is also true of the SEI platforms for stack Q's less than 1000. See Seismic Isolation DRD, LIGO-T960065-02-D, and Locally Damped Test Mass Motion, LIGO-T970092-00-D.

3 REQUIREMENTS

3.1. Characteristics

3.1.1. Performance Characteristics

3.1.1.1 Scattered Light

3.1.1.1.1 Scattered light requirements

- *The scattered light phase noise shall not exceed 1/10 the initial LIGO sensitivity as given in the LIGO Science Requirements Document: LIGO-E950018-02-E.*

Light scattered from baffles and other optical elements whose rays lie within the Rayleigh solid angle of the interferometer cavity will cause phase noise on the IFO output signal. The amplitude of the phase noise is proportional to the rms amplitude of the horizontal motion of the scattering surface and to the rms electric field amplitude injected into the IFO. This assumes motions small compared to a wavelength of the light; this is a valid assumption for stack Qs less than 1000.

Three categories of scattered light, in decreasing order of amplitude, are considered: 1) scattering from windows, beam-dumps, and baffles mounted *on the vacuum housing*, 2) scattering from beam-dumps and baffles mounted on *SEI optical platforms*, and 3) scattering from *SUS COCs*.

The most significant scattered light noise sources arise from 1) the APS beam which is backscattered from the output window and the optical surfaces in the ISC subsystems back onto the BS, 2) the BS PO beam and the two ITM PO beams which backscatter from the output windows mounted on the vacuum housing and the optical surfaces in the ADC/LSC into the recycling cavity, and 3) the two ETM PO beams which backscatter from the output window mounted on the vacuum housing and the optical surfaces in the ADC/LSC into the arm cavity. These six scattered light noise sources account for over 98% of the scattered light noise.

Light scattered from the SEI mounted surfaces have a factor 10^{-5} smaller amplitude than vacuum-mounted surfaces, and can be neglected by comparison. Light scattered from SUS suspended surfaces have an even smaller noise amplitude and can also be neglected.

In general the COC ghost beam light backscattered from an external surface into the solid angle of the IFO is proportional: 1) to the light power incident on the scattering surface P_i, 2) to a transmission factor T which accounts for the return-trip transmission through the COC element which produced the ghost beam, 3) to the cosine of the incident angle θ_{iwo} at the surface, 4) to the BRDF of the surface, 5) to the solid angle $\Delta\Omega$ of the IFO beam, and 6) to the added attenuation factor (if any) of the return path A_i.

$$P_s = P_i \cdot T \cdot [\cos\theta_{iwo} \cdot BRDF_{wo}(\theta_s)] \cdot \Delta\Omega \cdot \frac{1}{M^2} \cdot A_i$$

The demagnification factor M accounts for scattering from a reduced diameter beam, whenever the beam diameter is demagnified from the original IFO diameter by the COS output telescope or by optical elements in the ISC subsystem. The increase in solid angle with the decrease in beam diameter occurs because the product of solid angle and beam area is proportional to the total radiant flux and is an optical invariant; so as the beam area decreases, the solid angle increases proportionally. Therefore the solid angle of the beam divergence is inversely proportional to the square of the demagnification.

3.1.1.1.2 Summary of scattered light requirements

The scattered light requirements were calculated from the following equation:

$$(P_{si})_{REQ} \le P_0 \cdot \frac{F_i}{N_i \cdot K_i^2} \cdot \left(\frac{1}{10}\right)^2$$

The noise allocation factors F_i and the effective number of beams N_i scattering into a given scattering path were estimated by modeling all of the anticipated scattering sources and paths (See Core Optics Support Conceptual Design, LIGO-T970072-00-D). The noise strength parameters K_i are discussed in the appendix. See “Ki Values” on page 40. The following parameters were assumed.

recycling cavity gain, $G_{rc} = 50$
M = 0.01389
BRDF =.001
$\Delta\Omega = 2.7\times10^{-10}$ sr^{-1}.
$A_{Fi} = 0.001$, APS and SPS Faraday isolators
$P_0 = 6$ w

ratio of antisymmetric port signal to input laser power, $\frac{P_{APS}}{P_0} = 0.05$

ratio of symmetric port signal to input laser power, $\frac{P_{SPS}}{P_0} = 0.02$

The scattered light requirements are allocated approximately 98% to the principal scattering paths proportionally to the relative magnitudes of the particular paths, and 2% equally to all other scattering paths. The noise allocation factors are discussed in the appendix. See “Noise Allocation Factor” on page 38.

Details of the scattered light calculations are presented in the appendix. See “Scattered light noise Requirements” on page 30. A summary of the scattered light power, noise power allocation and scattering requirements for all the scattering sources is shown in Table 5, “Summary of Ghost Beam Scattered Light Requirements,” on page 13. It was assumed that if the beam was not dumped, or detected by ISC; it would undergo a glint back into the IFO. See “Ghost Beam Glint Calculations” on page 41.

Table 5: Summary of Ghost Beam Scattered Light Requirements

Ghost beam		scattering surface	vh-mounted surface scattered power into IFO, watt	rms noise amplitude ratio	scattered power allocation factor	scattered light power requirement, watt
RM	GBAR1	glint	scattered toward PSL	NA	NA	1.0E-06
RM	GBAR3	beam-dump	3.8E-23	1.2E-07	1.0E-03	5.8E-13
RM	GBAR4	glint	4.0E-18	4.8E-09	1.0E-03	5.8E-13
RM	SPS-vh-rc	ISC	1.8E-12	5.5E-03	4.0E-03	2.4E-12
BS	APS-vh-rc	ISC	3.3E-13	7.0E-02	5.0E-01	3.3E-13
BS	GBHR3x PO	ISC	2.1E-14	1.8E-02	3.1E-02	2.1E-14
ITMx	GBAR3 PO	ISC	1.5E-13	4.7E-02	2.2E-01	1.5E-13
ITMy	GBAR3 PO	ISC	1.5E-13	4.7E-02	2.2E-01	1.5E-13
ETMx	GBAR2 PO	ISC	2.4E-12	1.3E-02	1.6E-02	2.4E-12
ETMy	GBAR2 PO	ISC	2.4E-12	1.3E-02	1.6E-02	2.4E-12
BS	GBHR3x'	beam-dump	1.4E-18	1.4E-04	1.0E-03	6.4E-16
BS	GBHR4x'	glint	5.7E-16	2.9E-03	1.0E-03	6.4E-16
BS	GBHR3y'	beam-dump	1.4E-18	1.4E-04	1.0E-03	6.4E-16
BS	GBHR4y'	glint	5.7E-16	2.9E-03	1.0E-03	6.4E-16
RM	GBHR3	beam-dump	3.8E-23	2.5E-08	1.0E-03	5.8E-13
RM	GBHR4	glint	1.2E-15	1.4E-4	1.0E-03	5.8E-13
ITMx	GBAR1	beam-dump	4.0E-17	7.7E-04	1.0E-03	6.8E-16
ITMx	GBAR4	beam-dump	3.0E-14	2.1E-02	1.0E-03	3.0E-14
ITMy	GBAR1	beam-dump	4.0E-17	7.7E-04	1.0E-03	6.8E-16
ITMy	GBAR4	beam-dump	3.0E-14	2.1E-02	1.0E-03	3.0E-14
BS	GBAR3x	beam-dump	2.8E-18	2.0E-04	1.0E-03	6.4E-16
BS	GBAR4x	glint	1.1E-15	4.1E-03	1.0E-03	6.4E-16
BS	GBHR4x	glint	1.1E-15	4.1E-03	1.0E-03	6.4E-16
BS	GBAR1x'	beam-dump	4.4E-19	8.1E-05	1.0E-03	6.4E-16
BS	GBAR3x'	beam-dump	2.7E-20	2.0E-05	1.0E-03	6.4E-16
BS	GBAR4x'	glint	5.7E-16	2.9E-03	1.0E-03	6.4E-16
BS	GBAR3y'	beam-dump	2.8E-20	2.0E-05	1.0E-03	6.4E-16

BS	GBAR4y'	glint	5.7E-16	2.9E-03	1.0E-03	6.4E-16
Ghost beam		*scattering surface*	*vh-mounted surface scattered power into IFO, watt*	*rms noise amplitude ratio*	*scattered power allocation factor*	*scattered light power requirement, watt*
ETMx	diffuse-vh-ETM	baffle	3.3E-19	1.1E-03	1.1E-03	3.2E-18
ITMx	diffuse-vh-ITM	baffle	3.3E-19	1.1E-03	1.1E-03	3.2E-18
ITMx	GBHR3	beam-dump	9.8E-21	1.8E-04	1.0E-03	2.9E-18
ITMx	GBHR4	beam-dump	9.2E-27	1.8E-07	1.0E-03	2.9E-18
ETMx	GBHR3	glint	3.8E-20	3.6E-04	1.0E-03	2.9E-18
ETMx	GBHR4	glint	3.8E-26	3.6E-07	1.0E-03	2.9E-18
ETMy	diffuse-vh-ETM	baffle	3.3E-19	1.1E-03	1.1E-03	3.2E-18
ITMy	diffuse-vh-ITM	baffle	3.3E-19	1.1E-03	1.1E-03	3.2E-18
ITMy	GBHR3	beam-dump	9.8E-21	1.8E-04	1.0E-03	2.9E-18
ITMy	GBHR4	beam-dump	9.2E-27	1.8E-07	1.0E-03	2.9E-18
ETMy	GBHR3	glint	3.8E-20	3.6E-04	1.0E-03	2.9E-18
ETMy	GBHR4	glint	3.8E-26	3.6E-07	1.0E-03	2.9E-18
ETMx	GBAR3	beam-dump	4.6E-20	1.8E-06	1.0E-03	1.4E-13
ETMx	GBAR4	glint	9.5E-17	8.0E-05	1.0E-03	1.4E-13
ETMy	GBAR3	beam-dump	4.6E-20	1.8E-06	1.0E-03	1.4E-13
ETMy	GBAR4	glint	9.5E-17	8.0E-05	1.0E-03	1.4E-13
total noise budget (requirement < 0.1)				**0.10461**		

The scattering requirements for the 4K and 2K IFO at three different frequencies are shown in the following table (See “Scattered Light Requirements for Significant Scattering Paths for Three Different Frequencies- 4K IFO and 2K IFO” on page 15.).

Table 6: Scattered Light Requirements for Significant Scattering Paths for Three Different Frequencies- 4K IFO and 2K IFO

scattering path	*effective no. of beams*	*scattered power allocation factor*	*scattering requirement per source, watt* P_{si}		
			30 Hz	*100 Hz*	*1000Hz*
$P_{APS\text{-}vh\text{-}BS}$	1	0.50	$<3.3\times10^{-13}$	$<3.3\times10^{-13}$	$< 8.3x10^{-8}$
$P_{BSPO\text{-}vh\text{-}BS}$	1	0.031	$<2.1\times10^{-14}$	$<2.1\times10^{-14}$	$< 5.2x10^{-9}$
$P_{ITMPO\text{-}vh\text{-}ITM}$	2	0.22	$<1.5\times10^{-13}$	$<1.5\times10^{-13}$	$< 3.6x10^{-8}$
$P_{ETM\text{-}vh\text{-}ETM}$	2	0.016	$<2.4\times10^{-12}$	$<2.4\times10^{-12}$	$< 6.0x10^{-7}$

3.1.1.1.3 Implied BRDF of the scattering surface

The scattered light requirements place an implied requirement on the effective BRDF of all surfaces in the demagnified path of the COC PO and ghost beams.

$$BRDF_i(\theta_s) \cdot \frac{1}{M^2} = \left(\frac{P_i}{(P_s)_{REQ}} \cdot T \cdot [\cos\theta_i] \cdot \Delta\Omega \cdot A_i\right)^{-1}$$

The maximum allowed BRDF is proportional to the demagnification factor squared, inversely proportional to the rms motion of the surface squared, and proportional to the attenuation factor of the round trip path into the IFO. The implied requirements for the BRDF of the major paths are:

$$BRDF_{ITMPO} = 8\times10^{-4} \cdot \frac{1\times10^{-22}}{x^2{}_{vh}} \cdot \frac{M^2}{(0.0139)^2} \cdot \frac{1\times10^{-6}}{R^2{}_{ITMAR}} sr^{-1}$$

$$BRDF_{APS} = 8\times10^{-4} \cdot \frac{1\times10^{-22}}{x^2{}_{vh}} \cdot \frac{M^2}{(0.0139)^2} \cdot \frac{1\times10^{-3}}{A_{Fi}} sr^{-1}$$

$$BRDF_{ETMPO} = 8\times10^{-4} \cdot \frac{1\times10^{-22}}{x^2{}_{vh}} \cdot \frac{M^2}{(0.0139)^2} \cdot \frac{0.04}{T^2{}_{ETMND}} sr^{-1} \quad ,$$

where R_{ITMAR} is the reflectivity of the ITM AR coating, and T_{ETMND} , is the transmissivity of the ND filter in the ETM PO path.

3.1.1.2 Aperturing of main beam by COS elements, Requirement

Beam baffles and PO beam optics apertures shall not aperture the main beam at a diameter less than the 1 ppm Gaussian beam profile diameter (d_{1ppm} = 5.257w); i.e. 1ppm diameter >19.2 cm at the RM, BS, and ITM positions, and > 24.0 cm at the ETM position (see Core Optics Components, DRD LIGO-E950099-03-D).

3.1.1.3 Requirements for beam-dumps

There are four requirements which must be established regarding the dumping of COC ghost beams: 1) the beam-dump surface BRDF requirement, 2) the mounting location of the beam-dump surface; i.e. must the beam-dump surface be mounted on an SEI platform, or can it be mounted on the vacuum housing, 3) the minimum list of ghost beams which must be dumped, and 4) the attenuation requirement for the beam-dump.

3.1.1.3.1 Beam-dump BRDF Requirement

The beam-dump will be assumed to be mounted on the vacuum housing for a worst case analysis. The ITM $GBAR_1$ ghost beams which are backscattered by the beam-dump apparatus, as shown in figure 4, are the strongest scattered light phase noise sources of all the scattered COC ghost beams.

The BRDF for the ITM $GBAR_1$ beam-dump can be calculated as follows:

$P_i = 0.150$, watt

$P_s)_{REQ} = 6.8\times10^{-16}$

$T_{ITMAR} = 1\times10^{-3}$

$\Delta\Omega = 2.7\times10^{-10}$, sr^{-1}

$$BRDF_{bd}(\theta_s) = \left(\frac{P_i}{(P_s)_{REQ}} \cdot T_{ITMAR} \cdot [\cos\theta_i] \cdot \Delta\Omega\right)^{-1}$$

$BRDF_{bd} = 1.7\times10^{-2}$ sr^{-1}

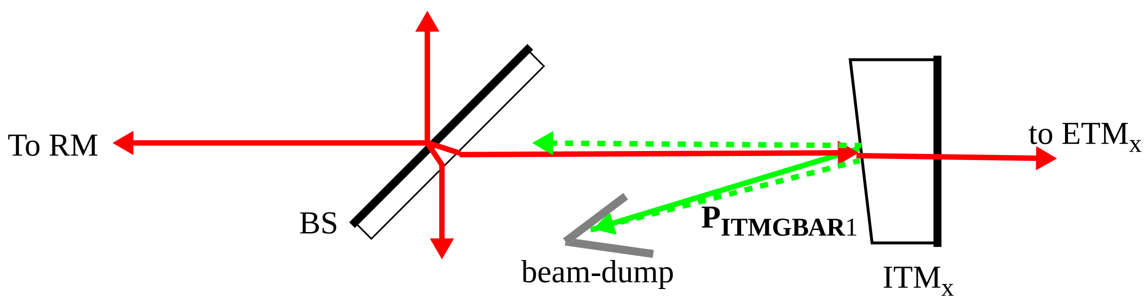


Figure 4: GB_3 Beam-dump

Therefore

the BRDF Requirement for the beam-dump surface shall be < $1.7\text{x}10^{-2}$ sr^{-1} .

3.1.1.3.2 Beam-dump mounting location requirement

The beam-dump surface shall be mounted on the vacuum housing, to minimize the interfer-

ence with the COC elements on the SEI.

3.1.1.3.3 Requirements for determining which ghost beams shall be dumped

Spurious ghost beams which undergo a glint from the wall of the vacuum housing into the IFO shall not cause excessive phase noise.

The glint power into the IFO and the rms noise amplitude ratio for each undumped beam was calculated as described in the appendix. See "Ghost Beam Glint Calculations" on page 41. GB1 and GB3 ghost beams must be dumped in order to avoid excessive phase noise scattered into the IFO. It can be seen from the Table 7 on page 17 that the BSGBAR4x, BSGBHR4x, ITMxGBAR4, ITMyGBAR4, ITMxGBHR4, and ITMyGBHR4 beams *may* cause a glint into the IFO which exceeds the scattered light noise requirement, and therefore must also be dumped.

Table 7: Summary of Ghost Beam Scattered Light Powers

Ghost beam		*Power incident on scattering surface, watt*	*vh-mounted surface scattered power into IFO, watt*	*glint power into IFO, watt*	*glint rms noise amplitude ratio*	*scattered light power requirement, watt*	*disposition of ghost beam*
RM	GBAR1	6.00E-03	NA	1.46E-09	NA	1.0E-06	
power glint into laser path toward mode cleaner							
RM	GBAR3	5.6E-03	1.5E-18		5.0E-06	5.8E-13	
RM	GBAR4	5.5E-06		1.2E-15	1.4E-04	5.8E-13	
RM	SPS-vh-rc	1.20E-01	1.8E-12		5.5E-03	2.4E-12	ISC
BS	ASY-vh-rc	3.00E-01	3.3E-13		6.9E-02	3.3E-13	ISC
BS	GBHR3x PO	7.50E-02	2.1E-14		1.7E-02	2.1E-14	ISC
ITMx	GBAR3 PO	1.41E-01	1.5E-13		4.6E-02	1.5E-13	ISC
ITMy	GBAR3 PO	1.41E-01	1.5E-13		4.6E-02	1.5E-13	ISC
ETMx	GBAR2 PO	3.93E-01	2.4E-12		1.4E-02	2.4E-12	ISC
ETMy	GBAR2 PO	3.93E-01	2.4E-12		1.4E-02	2.4E-12	ISC
BS	GBHR3x'	3.75E-02	1.4E-18		1.4E-04	6.4E-16	beam-dump
BS	GBHR4x'	1.87E-05		5.7E-16	2.9E-03	6.4E-16	
BS	GBHR3y'	3.75E-02	1.4E-18		1.4E-04	6.4E-16	beam-dump
BS	GBHR4y'	1.88E-05		5.7E-16	2.9E-03	6.4E-16	
RM	GBHR3	1.80E-04	8.3E-22		1.2E-07	5.8E-13	beam-dump
RM	GBHR4	1.74E-07		1.2E-18	4.5E-06	5.8E-13	
ITMx	GBAR1	1.50E-01	4.0E-17		7.7E-04	6.8E-16	beam-dump
ITMx	**GBAR4**	**1.37E-04**	**3.3E-23**	**3.0E-14**	**2.1E-02**	**6.8E-16**	**beam-dump**
ITMy	GBAR1	1.50E-01	4.0E-17		7.7E-04	6.8E-16	beam-dump
ITMy	**GBAR4**	**1.37E-04**	**3.3E-23**	**3.0E-14**	**2.1E-02**	**6.8E-16**	**beam-dump**

Ghost beam		*Power incident on scattering surface, watt*	*vh-mounted surface scattered power into IFO, watt*	*glint power into IFO, watt*	*GB4 undumped, rms noise amplitude ratio*	*scattered light power requirement, watt*	*disposition of ghost beam*
BS	GBAR3x	7.49E-02	2.8E-18		2.0E-04	6.4E-16	beam-dump
BS	**GBAR4x**	**3.75E-05**	**6.9E-25**	**1.1E-15**	**4.1E-03**	**6.4E-16**	**beam-dump**
BS	**GBHR4x**	**3.75E-05**	**6.9E-25**	**1.1E-15**	**4.1E-03**	**6.4E-16**	**beam-dump**
BS	GBAR1x'	1.50E-01	4.4E-19		8.1E-05	6.4E-16	beam-dump
BS	GBAR3x'	3.74E-02	2.7E-20		2.0E-05	6.4E-16	beam-dump
BS	GBAR4x'	1.87E-05	6.9E-27	5.7E-16	2.9E-03	6.4E-16	
BS	GBAR3y'	3.75E-02	2.8E-20		2.0E-05	6.4E-16	beam-dump
BS	GBAR4y'	1.87E-05	6.9E-27	5.7E-16	2.9E-03	6.4E-16	
ETMx	diffuse-vh-ETM	1.00E-01	3.3E-19		1.1E-03	3.2E-18	baffle
ITMx	diffuse-vh-ITM	1.00E-01	3.3E-19		1.1E-03	3.2E-18	baffle
ITMx	GBHR3	4.36E-03	9.8E-21		1.8E-04	2.9E-18	beam-dump
ITMx	**GBHR4**	**4.23E-06**	**9.2E-27**	**2.9E-17**	**1.8E-07**	**2.9E-18**	beam-dump
ETMx	GBHR3	7.87E-09		3.8E-20	3.6E-04	2.9E-18	
ETMx	GBHR4	7.87E-12		3.8E-26	3.6E-07	2.9E-18	
ETMy	diffuse-vh-ETM	1.00E-01	3.3E-19		1.1E-03	3.2E-18	baffle
ITMy	diffuse-vh-ITM	1.00E-01	3.3E-19		1.1E-03	3.2E-18	baffle
ITMy	GBHR3	4.36E-03	9.8E-21		1.8E-04	2.9E-18	beam-dump
ITMy	**GBHR4**	**4.23E-06**	**9.2E-27**	**2.9E-17**	**1.8E-07**	**2.9E-18**	beam-dump
ETMy	GBHR3	7.87E-09		3.8E-20	3.6E-04	2.9E-18	
ETMy	GBHR4	7.87E-12		3.8E-26	3.6E-07	2.9E-18	
ETMx	GBAR3	3.93E-04	4.6E-20		1.8E-06	1.4E-13	beam-dump
ETMx	GBAR4	3.93E-07		9.5E-17	8.0E-05	1.4E-13	
ETMy	GBAR3	3.93E-04	4.6E-20		1.8E-06	1.4E-13	beam-dump
ETMy	GBAR4	3.93E-07	4.6E-26	9.5E-17	8.0E-05	1.4E-13	
total noise budget (requirement < 0.1)					**0.1**		

All GB1, and GB3 beams from the BS, ITM, and ETM shall be dumped. In addition RM GBHR3, ITMxGBAR4, ITMyGBAR4, ITMxGBHR4, and ITMyGBHR4 shall be dumped

3.1.1.3.4 Implied beam-dump reflectivity requirement

The criterion for determining the beam-dump reflectivity requirement will be that the beam reflected from the beam-dump shall not glint from a vacuum wall and reflect back through the beam-dump path into the IFO with a power which exceeds the scattered light requirement. We will assume the beam makes two reflections on the beam-dump surface before exiting.

The power of the ITM GBAR1 beam reflected from the beam-dump which glints from the surface of the vacuum housing wall and then re-reflects from the surface of the beam-dump back into the IFO is given by the following.

$$P_g = P_i \cdot \frac{2r\lambda}{\pi^2 w^2} \cdot (R_{bd})^4 \cdot R_{AR} \quad .$$

Solving for the beam-dump reflectivity,

$$R_{bd} \le \left(\frac{P_g)_{REQ}}{P_i} \cdot \frac{1}{R_{AR}} \cdot \frac{1}{\frac{2r\lambda}{\pi^2 w^2}} \right)^{\frac{1}{4}}$$

$P_i = 0.150$ watt
$P_g)_{REQ} \le 6.8\times10^{-16}$ watt, see Table 5 on page 13.
$r = 1.5$ m
$\lambda = 1.06\times10^{-6}$ m
$w = 0.0364$ m
$r = 1.5$ m

Then,

the Reflectivity Requirement for the beam-dump surface shall be $R_{bd} < 1.2\times10^{-2}$.

3.1.1.4 Requirement for Baffling of Stray Light

3.1.1.4.1 Baffling of the ITM and the ETM in the arm cavity

If the diffusely scattered light from the ETM were not blocked, it might hit the surfaces of the BSC vacuum housing and backscatter onto the ETM; then scatter again from the ETM into the IFO, as shown in figure 5. The stray light baffle is required to block the scattered light, and to attenuate it with the BRDF and absorptivity of the baffle wall.

In exactly the same manner, the un-blocked diffusely scattered light from the ITM might get injected in the IFO after rescattering from the ITM, as shown in figure 6.

> *Baffles shall be placed on the beam-tube sides of the ITM and ETM to intercept the diffusely scattered light from the COC, and to ensure that the light scattered back into the IFO shall be less than* $3.2\times10^{-18}\,watt$. (See “Summary of Ghost Beam Scattered Light Requirements” on page 13.).

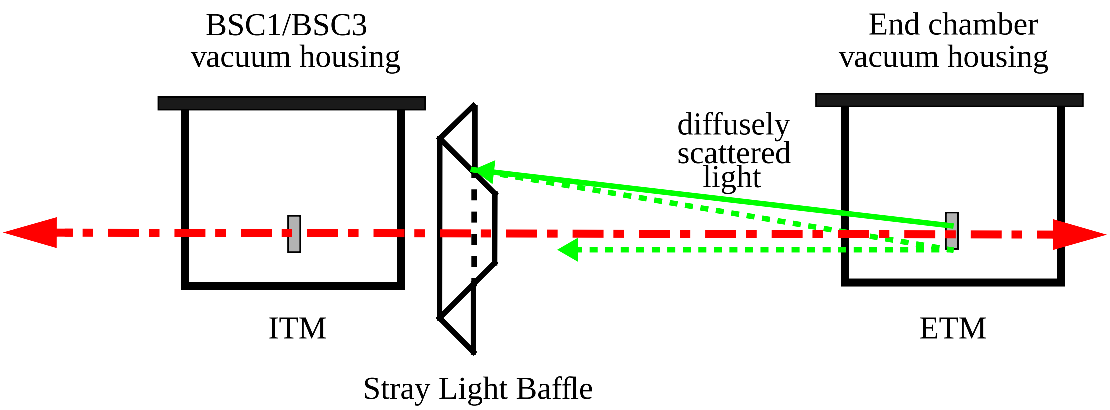


Figure 5: Diffuse Scattering from ETM, then Backscattered from the BSC Vacuum Housing, and Re-scattered by ETM into the IFO

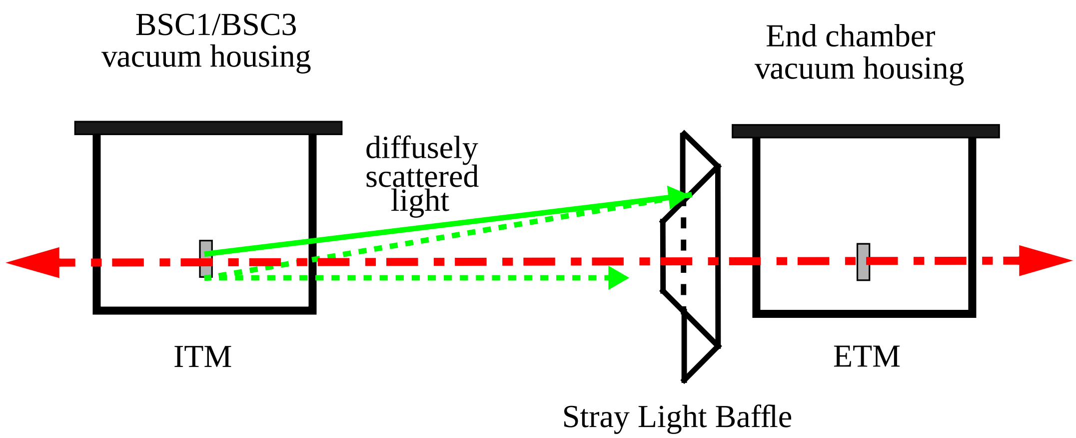


Figure 6: Diffuse Scattering from ITM, then Backscattered from the End Vacuum Housing, and Re-scattered by ITM into the IFO

3.1.1.4.1.1 Implied BRDF requirement of baffle surface

The implied BRDF of the baffle is given by the following; where $P_s)_{REQ}$ is the maximum allowed light power scattered off the baffle into the IFO from the diffusely scattered light of the COC, P_{diff} is the diffuse light scattered within the aperture of the beam tube, A_{COC} is the area of the COC, L is the length of the beam tube, and $BRDF_{COC}$ is the BRDF for scattering at the small angle subtended by the end of the beam tube into the Rayleigh cone of the IFO.

$$BRDF_{baff} = \left[\frac{P_{diff}}{P_s)_{REQ}} \cdot \frac{A_{COC}}{L^2} \cdot BRDF_{COC} \cdot \Delta\Omega \right]^{-1} .$$

The stray light baffles around the ETM and ITM shall have an implied $BRDF_{baff} \le 3.9 \times 10^{-2}\ sr^{-1}$.

3.1.1.4.1.2 Implied reflectivity requirement of baffle surface

The reflected light from the baffle surface which rescatters from the vacuum housing into the IFO must not exceed $3.2\times10^{-18} watt$ t. This places an implied reflectivity on the baffle surface given by the following:

$$R \le \left[\frac{P_{diff}}{P_s)_{REQ}} \cdot BRDF_{wall} \cdot \frac{A_{COC}}{L^2} \cdot BRDF_{COC} \cdot \Delta\Omega \right]^{-1}$$

Assuming $BRDF_{wall} = 0.1$, *the implied R<2.6;* i.e. *it doesn't matter how large the reflectivity of the baffle surface is.*

3.1.1.4.2 Baffle in Vacuum Manifold

3.1.1.4.2.1 Vacuum manifold scattering requirements

Diffusely scattered light from the COC will backscatter from the walls of the vacuum manifold segments, then rescatters off the COC into the IFO beam; as shown in figure 7. The requirement for the ETM and ITM diffuse scattering onto the vacuum housing for the initial LIGO has been determined (See "Summary of Ghost Beam Scattered Light Requirements" on page 13.) with an input laser power of 6 watts and a $K_{ac} = 4.5\times10^{6}$ for light scattered into the arm cavity.

$.(P_s)_{diffuse, vh, REQ, initialLIGO} = 4.2\times10^{-18} watt$.

Since the strain sensitivity of the enhanced LIGO is approximately two orders of magnitude below the initial LIGO sensitivity (See SRD LIGO-E950018-02-E), the scattered power requirement for the ultimate sensitivity will be four orders of magnitude smaller, i.e.

$(P_s)_{diffuse, vh, REQ, enhancedLIGO} = 4.2\times10^{-22} watt$

In order to meet the enhanced LIGO requirements, the requirement for scattered power into the IFO from vacuum manifold segments and attached components shall be < $4.2x10^{-22}$ watt

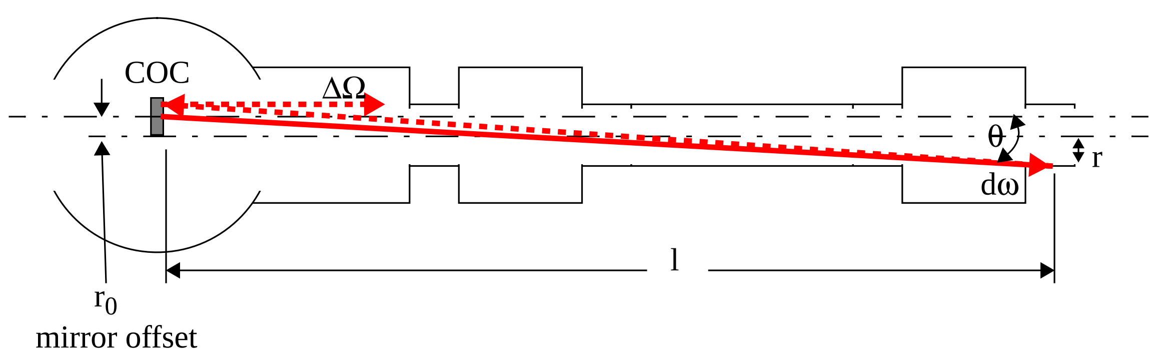


Figure 7: Vacuum manifold scattering geometry

3.1.1.5 COC Wedge Angle Requirements for 4K IFO

The COC wedge angle requirements have been established by LIGO Detector System Engineering. See Determination of the Wedge Angles for the Core Optics Components, T970091-00-D. They are the minimum wedge angles which will enable an adequate separation of the PO beams from the main beam at the appropriate pick-off locations. Adequate separation is defined as > 5cm separation between the 1ppm edge of the main beam and the 100ppm edge of the PO beam.

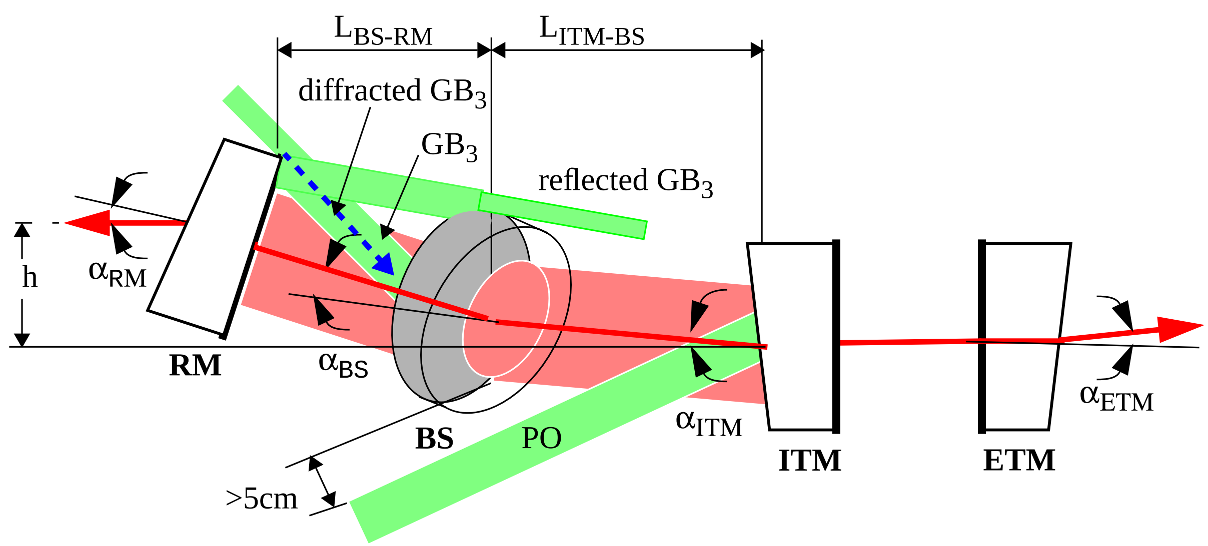


Figure 8: Separation of ITM PO and BS GB Beams caused by the COC Wedge Angles

3.1.1.6 COC Wedge Angle Requirements for 2K IFO

The wedge requirements for the 2K IFO are similar to the 4K IFO.

The $1°$ 2K BS wedge angle is too small to allow the separation of the BSGB1 and BSGB3 from the RM. These beams will reflect from the RM and partially from the BS before finally hitting the beam-dump. This is shown schematically in figure 8.

The ghost beams diffracted from the edges of the RM, BS and the BS beam-dump shall not exceed the scattered light requirements.

3.1.1.6.1 COC wedge angle requirements summary

The wedge angle requirements and calculated values for the optical axis deviation angles and optical centerline heights above the ITM-ETM optical centerline at the COC locations are summarized in Table 8 on page 23 and Table 9 on page 23 for the 4K and 2K IFO respectively. See Determination of the Wedge Angles for the Core Optics Components, T970091-00-D

..

Table 8: 4K IFO Core Optics Wedge Angle Characteristics

Component	*Wedge Angle*	*axis deviation angle*	*COC height above ITM-ETM axis*	*Distance to pick-off location*	*Separation margin of PO from main beam*
RM	$2°24' \pm 5'$	$-1.083°$	8.7 cm	2.0 m	7.1 cm
BS	$1° \pm 5'$	$0.558°$	4.4 cm	4.8 m	8.6cm
ITM	$1°10' \pm 5'$	$0.525°$	0.0 cm	4.8 m	10.9 cm
ETM	$2° \pm 5'$	$0.899°$	0.0 cm	2.0 m	2.9 cm

Table 9: 2K IFO Core Optics Wedge Angle Characteristics

Component	*Wedge Angle*	*axis deviation angle*	*COC height above ITM-ETM center line*	*Distance to pick-off location*	*Separation margin of PO from main beam*
RM	$2°24' \pm 5'$	$-1.083°$	14.7 cm	2.8 m	16.9 cm
BS	$1° \pm 5'$	$0.558°$	8.7 cm	3.0 m	-12.8 cm (see note below)
FM		$0.269°$	0.2		
ITM	$34' \pm 5'$	$0.255°$	0.0 cm	9.3 m	9.3 cm
ETM	$2° \pm 5'$	$0.899°$	0.0 cm	2.0 m	2.9 cm

note: The distance from the BS wedge to the pick-off location is too close for the ghost beam to separate sufficiently from the main beam. The GB_{BSAR1} will make a first reflection from the RM and a second reflection from the BS before finally being dumped at the beam-dump located back at the ITM position.

3.1.1.7 *PO beam-reducing telescope design requirements*

The PO beam-reducing telescope shall transform the input IFO beam into a collimated output beam with a Gaussian $1/e^2$ power radius of approximately 1mm, with the beam waist location within approximately 1000mm of the ISC WFS optical train.

The PO telescope shall be accomodated on the appropriate SEI platform, and shall not exceed the size, weight, and themal noise requirements of the SEI platform.

The PO telescope and its associated PO beam optical train shall not excessively distort the wavefront of the PO beam. Acceptable wavefront distortion will maintain the WFS signal contrast ratio > 5:1.

The PO telescope will function satisfactoraly with an input angular field-of-view of $\pm 4\times 10^{-4}$ rad.

3.1.1.8 Output Vacuum Window

Output vacuum windows will provide optical paths for PO beams out of the vacuum enclosure to interface with the ISC subsystems.

The scattered light power from each output window shall account for a negligible contribution to the total scattered light power that that particular PO beam path.

The wavefront distortion produced by each output window shall account for a negligible reduction of the WFS signal contrast ratio of that particular PO beam path.

3.1.2. Physical Characteristics

3.1.2.1 Vacuum compatibility of COS elements

3.1.2.1.1 Outgassing of COS elements

The COS elements shall be fabricated from materials whose outgassing properties are compatible with the vacuum requirements of the LIGO. See LIGO Vacuum Compatibility, Cleaning Methods and Procedures, LIGO-E960022-00-D

3.1.2.1.2 Vacuum pumping conductance of COS beam-dump/baffle

The COS beam-dump/baffle shall not significantly reduce the vacuum pumping conductance of the LIGO vacuum system.

3.1.2.2 Access for Optical lever beams and TV Camera Viewing of COCs

The beam-dump/baffle assemblies shall allow access to the optical lever beams and TV camera viewing of the COC elements. See ASC Optical Lever Design Requirement Document, LIGO-T950106-01-D

3.1.2.3 Optical Alignment of COS

The COS PO telescopes shall be pre-aligned before assembly into the IFO vacuum housing.

The COS telescopes and optical beam-dump/baffles shall be final aligned to the IFO optical centerline and ghost beam centerlines during the initial IFO optical alignment.

3.1.2.4 Resonant Frequency of COS Elements Mounted on the Optics Platform

The resonant frequencies and Q's of the beam-dump/baffle, pick-off beam telescope and accessory optics which are mounted to the optics platforms shall not cause excessive thermal-noise of the optical platform position.

The requirement for thermally induced noise amplitude impressed on the SEI platform is that it shall not exceed the SRD test mass noise requirement $x(\omega)_{REQ} < 1\times10^{-20} m/\sqrt{Hz}$ *, in the frequency band 30-1000Hz.* See LIGO Science Requirements Document, LIGO-E950018-02-E.

The minimum frequency which meets the thermal noise requirement $x(\omega_0)_{REQ}$ can be calculated at resonance from the following

$$(\omega_0)_{REQ} \geq \left[\frac{4k_BT}{M} \cdot \frac{m_i}{M} \cdot \frac{Q}{x(\omega_0)^2{}_{REQ}}\right]^{\frac{1}{3}} \quad m/\sqrt{Hz},$$

where m_i is the mass of the COS element and M_i is the mass of the SEI platform. See Seismic Isolation DRD, LIGO-T960065-02-D.

3.1.3. Interface Definitions

3.1.3.1 Interfaces to other LIGO detector subsystems

3.1.3.1.1 Mechanical Interfaces

3.1.3.1.1.1 Mounting of beam-dump/baffle assemblies and pick-off beam optics

The COS beam-dump/baffle assemblies and pick-off beam optics will be mounted to the appropriate optical platforms within the HAM and BSC housings. The mounting interface will be **TBD** bolt hole pattern and bolt hole thread size.

3.1.3.1.2 Electrical Interfaces

None

3.1.3.1.3 Optical Interfaces

3.1.3.1.3.1 COC interface

The COS ghost beams and pick-off beams originate as reflections of the main IFO beam from the AR and HR surfaces of the COCs and interface with the COC.

3.1.3.1.3.2 ISC *interface*

The COS pick-off beams will pass through the output window in the vacuum enclosure and interface with the ASC and LSC subsystems.

3.1.3.1.4 Stay Clear Zones

To preserve the quality of the ISC PO beams, it will be necessary to maintain a stay clear zone around the optical axes of the PO beams from the surface of the COC through the output window. The stay clear distance from the optical center line shall be > 130 mm in the primary beam and > 15 mm in the secondary beam at the output of the PO beam telescope.

3.1.3.2 Interfaces external to LIGO detector subsystems

3.1.3.2.1 Mechanical Interfaces

3.1.3.2.1.1 Baffle-ITM, 2K IFO

The COS beam-dump/baffle assembly for the ETM-side of the ITM in the 2K IFO will be mounted to the walls of the vacuum housing in the WB-1A and WB-2A tube transition sections by means of independent expansion ring assemblies, without modifying the vacuum housing.

3.1.3.2.1.2 Output vacuum window

The PO beam output windows will be mounted in existing optical ports of the BSC2, BSC4, HAM2, and HAM8. The mounting interface will be a standard conflat.

3.1.4. Reliability

- It is expected that the COS elements have no inherent hard failure mechanisms. Reliability will be dependent upon the telescope optical elements and the beam-dump surfaces remaining free of contamination and scratches.
- An adequate procedure for installing and aligning shall be developed to ensure the integrity of the COS elements.

3.1.5. Maintainability

Standard optical cleaning procedures will be adequate to maintain the cleanliness of the COS optical surfaces.

3.1.6. Environmental Conditions

The optical surfaces shall be kept clean until installation. The COS beam-dump/baffle assemblies will be baked out under conditions compatible with the LIGO beam tube bakeout procedures, and the vacuum cleanliness of the cleaned COS elements shall not be compromised before installation.

3.1.7. Transportability

The COS elements shall be transportable by commercial carrier without degradation in performance. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable by forklift.

3.2. Design and Construction

3.2.0.1 Finishes

TBD

3.2.0.2 Materials

TBD

3.2.0.3 Processes

TBD.

3.2.1. Component Naming

All components shall be identified using the LIGO Detector Naming Convention (document LIGO-E950111-A-E). This shall include identification physically on components, in all drawings and in all related documentation.

3.2.2. Workmanship

TBD

3.2.3. Interchangeability

TBD

3.2.4. Safety--TBD

This item 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 <u>LIGO Project System Safety Management Plan</u> LIGO-M950046-F, section 3.3.2.

3.3. Documentation

3.3.1. Specifications

TBD

3.3.2. Design Documents

TBD

3.3.3. Engineering Drawings and Associated Lists

TBD

3.3.4. Technical Manuals and Procedures

3.3.4.1 Procedures

TBD

3.3.5. Documentation Numbering

3.3.6. Test Plans and Procedures

3.4. Logistics

TBD.

3.5. Precedence

TBD

3.6. Qualification

Test and acceptance criteria TBD.

4 QUALITY ASSURANCE PROVISIONS

4.1. General

4.1.1. Responsibility for Tests

The COS task leader and designated Detector Group personnel will be responsible for all tests, their documentation and interpretation.

4.1.2. Special Tests

4.1.2.1 Engineering Tests

- Alignment test of PO telescopes.
- BRDF measurement of beam-dump surface

4.1.3. Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan. TBD

4.2. Quality conformance inspections

4.2.1. Inspections

Visual inspections of as-received telescope mirrors and beam-dump absorbing glass to verify scratch and dig specifications

5 PREPARATION FOR DELIVERY

5.1. Preparation

5.2. Packaging

5.3. Marking

APPENDIX 1

6 DISTORTION OF THE PO BEAMS

6.1. PO Beam Aperture Requirement

The WFS signal is derived by mixing the TEM_{00} and TEM_{01} beam components in the output PO beam on the surface of a split photodetector and subtracting the signals from each half. The fractional loss of signal resulting from aperturing the beam at a radius b can be modeled analytically as the integration of the product of the two Hermite-Gaussian polynomials over the two halves of the semi-infinite plane, as shown in the integral equation below.

$$\frac{\Delta WFS}{WFS} = \frac{\int_{-b}^{0} u_0 \cdot u_1 dxdy - \int_{0}^{b} u_0 \cdot u_1 dxdy}{\int_{-\infty}^{0} u_0 \cdot u_1 dxdy - \int_{0}^{\infty} u_0 \cdot u_1 dxdy}$$, where

u_0 is the TEM_{00} mode polynomial, u_1 is the TEM_{01} mode polynomial, and the limits of integration are taken over the left and right halves of the segmented photodetector.

For b = 2.1 w_0, which corresponds to aperturing the PO beam at the 1000 ppm power radius, the WFS error signal decreases by 1% from the signal obtained with an infinite aperture. If we accept a 1% decrease as acceptable, then this

- *establishes the requirement that the aperture diameter shall be > 1000ppm Gaussian beam* *profile diameter of the main beam.*

6.2. PO Beam Optical Train Wavefront Distortion Requirement

The PO beams are used by the ASC WFS system to obtain signals proportional to the relative tilt and displacement errors of the carrier and sideband beams within the IFO. Either a tilt detector or a displacement detector is formed by placing the WFS at the Guoy phase position which respectively maximizes the orthogonal tilt or displacement signals.

The optimum Guoy phase location for placing a tilt or displacement detector can be determined by calculating the displacement and tilt contrast ratios as defined below.

$R_D = \frac{S_{disp}}{S_{tilt}}$, and $R_T = \frac{S_{tilt}}{S_{disp}}$.

The ASC requirements for IFO mirror control place implied requirements that the tilt contrast ratio and displacement contrast ratios shall be >5.

The ASAP WFS model described in Effect of PO Telescope Aberrations on Wavefront Sensor Performance, LIGO-T980007-00-D, places an implied requirement on the aberrations in the PO beam optical train. In order to meet the ASC signal contrast ratio requirements,

- *the total rms sum of aberrations in the PO beam optical train shall be < 1 wave p-v at 632.8 nm wavelength.*

APPENDIX 2

7 SCATTERED LIGHT NOISE REQUIREMENTS

7.1. Basis for Noise Calculations

The COS scattered light requirements are based on the calculated scattered light-to-detector output voltage transfer coefficients presented in Secondary Light Noise Sources in LIGO, LIGO-T970074-00-D; on the noise amplitude parameters presented in Table 10, “Noise Amplitude Parameters in the Frequency Range 30<f<1000 Hz,” on page 31; and on the estimate of scattered light intensities from various scattering sources in the IFO, as calculated in COS Preliminary Design, LIGO-T980010-00-D

.

Table 10: Noise Amplitude Parameters in the Frequency Range 30<f<1000 Hz

Noise Amplitude Parameter	*30 Hz*	*100 Hz*	*1000Hz*
rms displacement amplitude of vacuum enclosure, $m/Hz^{1/2}$ --see SEI DRD	$x_{vac} < 1x10^{-10}$	$x_{vac} < 1x10^{-11}$	$x_{vac} < 1x10^{-13}$
initial LIGO sensitivity, m/Hz1/2-- see SRD	$X < 1x10^{-18}$	$X < 1x10^{-19}$	$X < 5x10^{-19}$
standard quantum limit, 1000Kg (SQL), $m/Hz^{1/2}$-- see SRD	$X_{SQL} < 5.3x10^{-21}$	$X_{SQL} < 1.6x10^{-21}$	$X_{SQL} < 1.6x10^{-22}$
horizontal SEI transfer function, see SEI DRD	$A_{SEI} < 6x10^{-5}$	$A_{SEI} < 1x10^{-5}$	NA
horizontal SUS transfer function, see SEI DRD	$A_{SUS} < 7x10^{-4}$	$A_{SUS} < 6x10^{-5}$	$A_{SUS} < 6x10^{-7}$
rms thermal displacement of SEI platform, $m/Hz^{1/2}$, see Motion of Optical Platforms Driven by Thermal Noise from Spring Elements, LIGO-T970055-00-D	NA	NA	$x_{SEIthermal} < 3x10^{-18}$

7.2. Requirement for Scattering from Vacuum Housing Mounted Surfaces

The expected backscattered power of all the ghost beams was calculated, assuming that they scatter from vacuum housing mounted surfaces; in order to estimate the fractional allocation of scattered light from the various scattering paths. The effective BRDF of the scattering surfaces in the demagnified ITM PO beam was assumed to be $BRDF_{ITM} = 8x10^{-4}\ sr^{-1}$.

7.2.1. APS beam scattering requirement

The APS beam is scattered by the output surfaces mounted on the vacuum housing, as shown schematically in figure 9. *Note that a Faraday isolator has been included to reduce the backscattered light to acceptable levels*. The expected backscattered power of the APS beam (Ps_{APS}) was calculated with the following equation.

$$Ps_{DPS} = P_0 \cdot \frac{P_{DPS}}{P_0} \cdot T_{BSAR} \cdot [\cos\theta_{iwo} \cdot BRDF_{wo}(\theta_s)] \cdot \Delta\Omega \cdot \frac{1}{M^2} \cdot A_{Fi}, \text{ where}$$

transmissivity of BS AR coating, $T_{BSAR} = 0.999$

scattering surface incidence angle	θ_{iwo} = 57 deg
de-magnification of the beam	M = 0.01389
power attenuation factor of the Faraday isolator	A_{Fi} = 0.001,
ratio of the APS signal to the input laser power,	$P_{DPS}/P_0 = 0.05$
laser power	$P_0 = 6 watts$
laser wavelength	$\lambda = 1.06\times10^{-6}$m
Gaussian beam parameter	$w_0 = 0.0364$ m.

scattering solid angle $\Delta\Omega = \frac{1}{\pi} \cdot \frac{\lambda^2}{w_0^2} = 2.7\times10^{-10} sr$

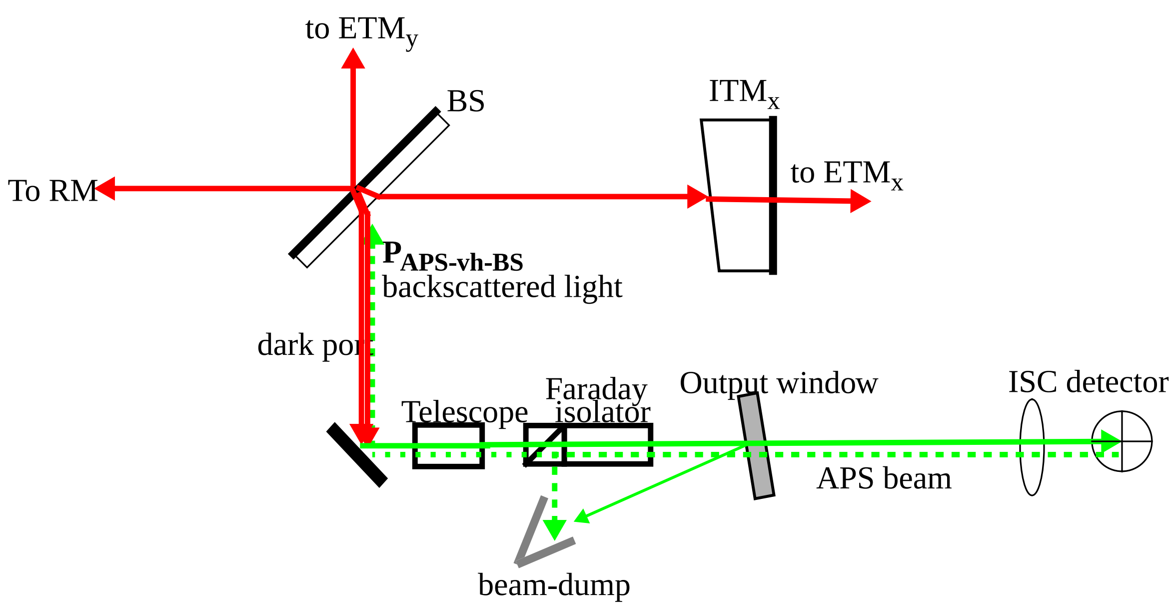


Figure 9: The Scattered APS Beam from the Output Window Mounted on the Vacuum Housing

Then $Ps_{APS} = 3.3\times10^{-13}$ watt,

and after determining the expected scattered light from all other scattering sources, the noise allocation factor for the APS beam was determined to be

$F_{APS} = 0.50$.

The scattered light requirement is given by

$$(P_{sAPS})_{REQ} \le P_0 \cdot \frac{F_i}{N_i \cdot K_i^2} \cdot \left(\frac{1}{10}\right)^2 ,$$

where $K_{DPS} = 3\times10^5$

is the proportionality factor between the photocurrent noise ratio and the root scattered light power ratio, and Ni=1. See “Noise Allocation Factor” on page 38. Then

$(P_{sAPS})_{REQ} \leq 3.3 \times 10^{-13}$ watt.

7.2.2. ITM PO beam scattering requirement

The PO beam of ITM_x back-scatters from the output window and injects a noise field into the symmetric side of the recycling cavity. Similarly, backscattering of the ITM_y PO beam injects noise into the antisymmetric side of the recycling cavity. This is shown functionally in figure 10.

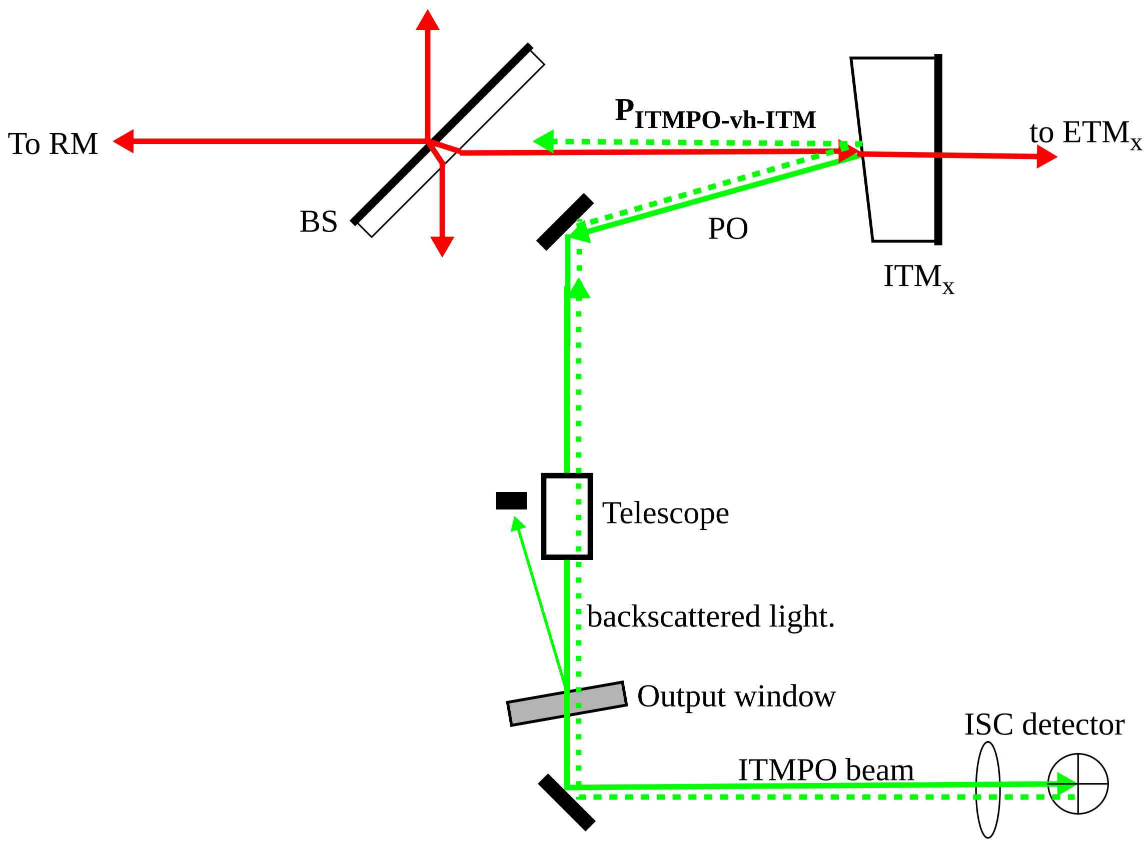


Figure 10: Backscattered light from ITM_x PO and ITM_y PO beams injects noise into the recycling cavity.

Note that the output window must be tipped in order to avoid a direct glint into the IFO from the parallel AR surfaces of the window. The scattered light power was calculated with the following equation.

$$P_{sITM} = P_0 \cdot \frac{1}{2} \cdot \left(\frac{P_i}{P}\right)^2_{ITMPO} \cdot G_{rc} \cdot [\cos\theta_{iwo} \cdot BRDF_{wo}(\theta_s)] \cdot \Delta\Omega \cdot \frac{1}{M^2} \quad ,$$

where

$$\left(\frac{P_i}{P}\right)_{ITMPO} = R_{ITMAR}$$

scattering surface incidence angle θ_{iwo} = 57 deg
magnification of the telescope M = 0.01389
scattering solid angle $\Delta\Omega = 2.7\times10^{-10}$ sr^{-1}.
reflectivity of ITM AR coating R_{ITMAR} =.001
recycling cavity gain G_{rc} = 50

Then $Ps_{ITM} = 1.5\times10^{-13}$ watt,

and after determining the expected scattered light from all other scattering sources, the noise allocation factor for the ITM PO beam was determined to be

$F_{ITM} = 0.22$.

The scattered light requirement is given by

$$(P_{sITM})_{REQ} \le P_0 \cdot \frac{F_i}{N_i \cdot K_i^2} \cdot \left(\frac{1}{10}\right)^2,$$

where $K_{ITM} = 3\times10^5$

is the proportionality factor between the photocurrent noise ratio and the root scattered light power ratio, and N_i=2. See “Noise Allocation Factor” on page 38. Then

$(P_{sITM})_{REQ} \le 1.5\times10^{-13}$ watt.

7.2.3. ETM PO beam scattering requirement

ETM PO beam backscatters into the arm cavity from the output surfaces mounted on the vacuum housing, as shown in Figure11

A neutral density attenuator is placed in the output PO beam after the telescope to attenuate the scattered light.

The expected backscattered power of the ETM PO beam Ps_{ETM} was calculated with the following equation.

$$P_{sETM} = P_0 \cdot \frac{1}{2} \cdot \left(\frac{P_i}{P}\right)^2_{ETMPO} \cdot G_{rc} \cdot T_{FP} \cdot T_{ND} \cdot [\cos\theta_{iwo} \cdot BRDF_{wo}(\theta_s)] \cdot \Delta\Omega \cdot \frac{1}{M^2},$$

$$\left(\frac{P_i}{P}\right)_{ETMPO} = T_{AR} ,$$

T_{ETMAR} = 0.999
T_{ETMHR} = 0.000020
R_{ETMHR} =.999980
R_{ITMHR} =.97
G_{rc} = 50
θ_{iwo} = 57 deg

M = 0.01389
$\Delta\Omega = 2.7\times10^{-10}$ sr^{-1}.

transmissivity of the Fabry-Perot arm cavity at resonance is

$$T_{FP} = \frac{(1 - R_{ITMHR}) \cdot (1 - R_{ETMHR})}{(1 - \sqrt{R_{ITMHR} \cdot R_{ETMHR}})^2} = 0.0026$$

.

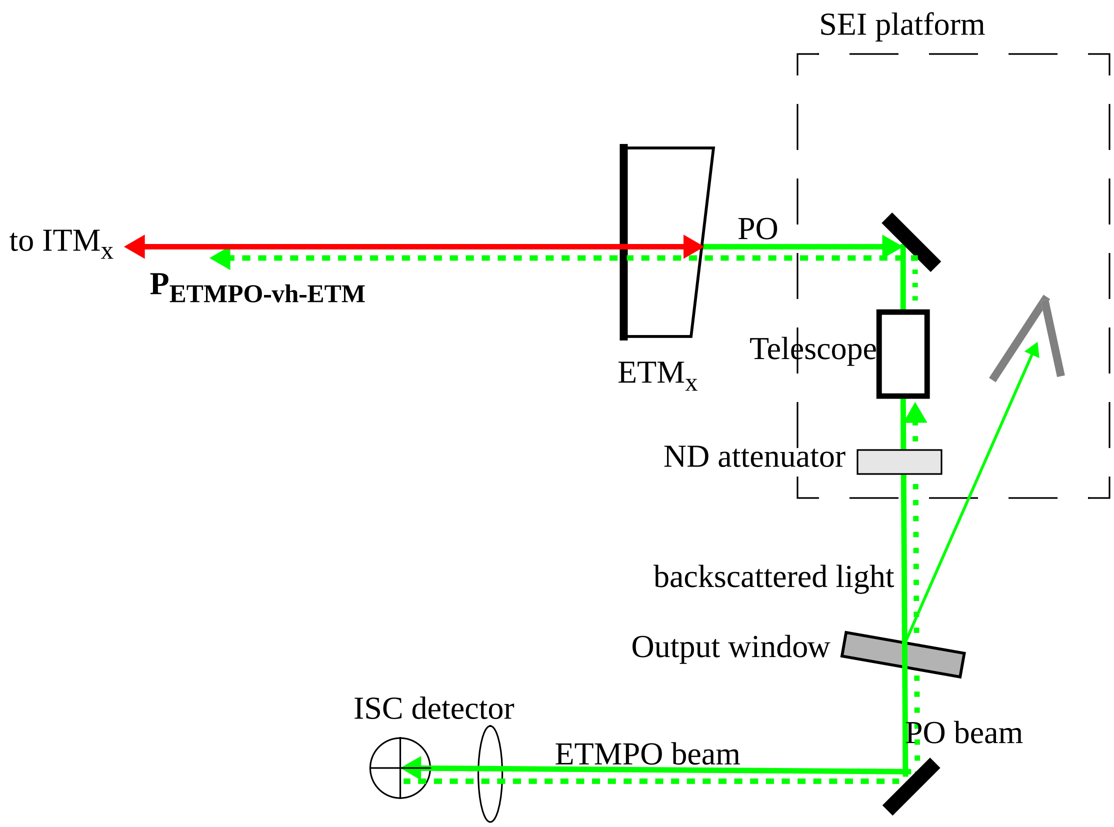


Figure 11: ETM PO beam backscattered into arm cavity from output window mounted on vacuum housing

transmissivity of neutral density filter $T_{ND} = 0.10$

Then $Ps_{ETM} = 2.4\times10^{-12}$ watt,

and after determining the expected scattered light from all other scattering sources, the noise allocation factor for the ETM PO beam was determined to be

$F_{ETM} = 0.02$.

The scattered light requirement is given by

$$(P_{sETM})_{REQ} \le P_0 \cdot \frac{F_i}{N_i \cdot K_i^2} \cdot \left(\frac{1}{10}\right)^2,$$

where $K_{ETM} = 2\times10^{4}$

is the proportionality factor between the photocurrent noise ratio and the root scattered light power ratio, and N_i=2. See “Noise Allocation Factor” on page 38. Then

$(P_{sETM})_{REQ} \le 2.4\times10^{-12}$ watt.

7.2.4. SPS beam scattering requirement

The SPS beam will scatter from the surfaces of the output window and inject noise into the recycling cavity through the RM, as shown in figure 12.

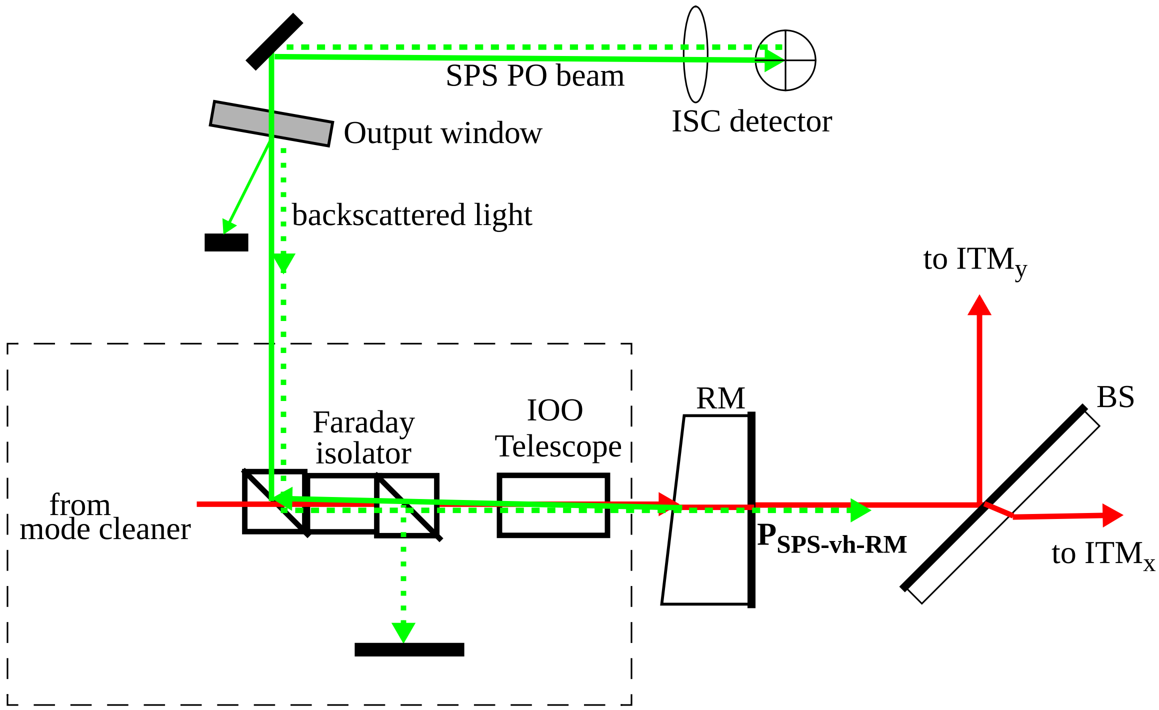


Figure 12: RM SPS beam backscattered into recycling cavity from output window mounted on vacuum housing

The expected backscattered power of the SPS PO beam Ps_{SPS} was calculated with the following equation.

$$P_{sSPS} = P_0 \cdot \left(\frac{P_{SPS}}{P_0}\right) \cdot T_{HR} \cdot T_{AR} \cdot [\cos\theta_{iwo} \cdot BRDF_{wo}(\theta_s)] \cdot \Delta\Omega \cdot \frac{1}{M^2} \cdot A_{Fi} \quad ,$$

ratio of the SPS signal to the input laser power, $\frac{P_{SPS}}{P_0} = 0.02$

A_{Fi} =0.001

T_{RMAR} = 0.999

T_{RMHR} = 0.03

θ_{iwo} = 57 deg

M = 0.05
$\Delta\Omega = 2.7\times10^{-10}$ sr^{-1}.

Then $Ps_{SPS} = 1.8\times10^{-12}$ watt,

The scattered light requirement is given by

$$(P_{sSPS})_{REQ} \le P_0 \cdot \frac{F_i}{N_i \cdot K_i^2} \cdot \left(\frac{1}{10}\right)^2 ,$$

where $K_{SPS} = 1\times10^{4}$, N_i=1, and F_i=0.004. See "Noise Allocation Factor" on page 38. Then $(P_{sSPS})_{REQ} \le 2.4\times10^{-12}$ watt.

7.2.5. Requirement for glinting RM GBAR1 toward the laser

The RM GBAR1 ghost beam may glint from the surface of the vacuum chamber and reflect in the beam direction toward the laser. The glint beam must pass through the mode cleaner Faraday isolator, and through two more Faraday isolators before entering the laser cavity. The combined attenuation of three isolators will be 1E9. We will assume that the laser can tolerate an injected power of 1E-15 watt without causing a laser noise problem.

Therefore, the requirement for the glint of light from the RMGBAR1 toward the laser shall be less than 1E-6 watt.

7.3. Requirement for scattering from SEI mounted surfaces

The horizontal displacement amplitude of the SEI platform @ 100 Hz is smaller than the vacuum housing displacement by a factor 10^{-5}, the SEI horizontal transfer function (See "Noise Amplitude Parameters in the Frequency Range 30<f<1000 Hz" on page 31.). Thermal noise dominates the motion of the SEI platform at 1000 Hz, and the thermally induced displacement amplitude of the SEI platform @ 1000 Hz is estimated to be a factor $3\text{x}10^{-5}$ smaller than the vacuum housing displacement (See "Noise Amplitude Parameters in the Frequency Range 30<f<1000 Hz" on page 31.).

Since the phase noise power is proportional to the displacement squared; for similar scattered intensities, the phase noise power due to scattering from SEI mounted surfaces in the frequency band 100Hz to 1000Hz is 10^{-10} times smaller than the noise power due to scattering from vacuum housing mounted surfaces.

- *Therefore the scattered light from SEI mounted surfaces shall be ignored*.

7.4. Requirement for scattering from SUS mounted surfaces

The COC are suspended from the SUS which are mounted to the SEI optical platforms. The horizontal displacement *amplitude* of the COC @ 100Hz is a factor $A_{SEI} \cdot A_{SUS} = 6\times10^{-10}$ smaller than the vacuum housing displacement. At 1000 Hz the combined motion of the suspended COC from all sources is at least a factor 10^{-7} smaller than the vacuum housing displacement (see

Table 10, “Noise Amplitude Parameters in the Frequency Range 30<f<1000 Hz,” on page 31). Then for similar scattered intensities, the phase noise *power* due to scattering from SUS mounted surfaces in the frequency band 100Hz to 1000Hz will be at least a factor 10^{-14} smaller than the scattering from surfaces mounted to the vacuum housing.

- *Therefore the internal ghost beams that scatter from the surfaces of the COC can be ignored in comparison with scattering of PO beams from output windows.*

7.5. Noise Allocation Factor

The scattered light from each of the various paths contributes to the total scattered light phase noise. Some paths contribute more noise than other paths, so a systematic approach to allocating the noise budget will be developed in the following. The APS scattered light phase noise current will be calculated as an example, and the results will be generalized to include all the other noise sources.

The photodetector current at the antisymmetric port output resulting from the scattered light field combining with the carrier light field on the surface of the BS is proportional to 1) the phase modulation of the light caused by the in-band horizontal displacement of the scattering surface, and to 2) the field amplitude of the scattered light reflecting from the ITM onto the BS.

$$i_{sDPS} \propto \sqrt{RP_{sDPS}} \cdot \frac{4\pi x_{vh}(f)}{\lambda}$$

P_{sAPS}, is the light backscattered through the dark port into the IFO; R, is the reflectivity of the FP; and $x_{vh}(f)$, is the horizontal displacement of scattering surface.

The photodetector current which carries the gravity wave signal is proportional to 1) the phase modulation of the arm cavity light caused by the differential displacement of the IFO, which is increased by the storage time of the light in the arm cavity at the gravity wave frequency, and 2) to the field amplitude of the carrier light at the BS.

$$i_g \propto \sqrt{P_{BS}} \cdot \frac{4\pi X(f)}{\lambda} \cdot \frac{2}{T\sqrt{1 + \left(\frac{f}{f_0}\right)^2}}$$

The carrier light power on the BS is greater than the input laser power at the RM by the recycling cavity gain factor, $P_{BS} = G_{rc} \cdot P_0$

X(f), is the gravity wave differential displacement; G_{rc}, is the gain of recycling cavity; P_0, is the laser power incident on the RM; and T, is the transmissivity of the ITM.

The ratio of the scattered light noise current to the gravity wave signal current is given by

$$\frac{i_{sDPS}}{i_g} = \left(\frac{T}{2}\sqrt{R\left(1 + \left(\frac{f}{f_0}\right)^2\right)} \cdot \frac{x(f)}{X(f))} \cdot \frac{1}{\sqrt{G_{rc}}}\right)\sqrt{\frac{P_{sDPS}}{P_0}} = K_{DPS}\sqrt{\frac{P_{sDPS}}{P_0}}$$

The noise/signal current ratio is proportional to the square root of the scattered light/input laser light power, where the proportionality constant is defined by

$$K_{DPS} = \frac{T}{2}\sqrt{R\left(1+\left(\frac{f}{f_0}\right)^2\right)}\cdot\frac{x(f)}{X(f))}\cdot\frac{1}{\sqrt{G_{rc}}}$$

The K_{APS} value was evaluated at 100 Hz using the IFO displacement at the minimum initial LIGO sensitivity, and the seismic motion defined in the SRD,

$$X_{SRD}(100Hz) = 1\times10^{-19}\frac{m}{\sqrt{Hz}}, x_{vh}(100Hz) = 1\times10^{-11}\frac{m}{\sqrt{Hz}}$$
$$K_{DPS} = 3\times10^5.$$

The noise/signal power ratio for any typical scattering path can be described by a similar K value. (See Secondary Light Noise Sources in LIGO, LIGO-T970074-00-D.)

$\left(\frac{is_i}{i_{gSRD}}\right)^2 = K_i^{\ 2}\cdot\frac{P_{si}}{P_0}$, and the total noise/signal power is additive.

$$\left(\frac{is}{i_{gSRD}}\right)^2 = N_1\cdot K^2{}_1\cdot\frac{P_{s1}}{P_0}+N_2\cdot K^2{}_2\cdot\frac{P_{s2}}{P_0}+\ldots+N_m\cdot K^2{}_m\cdot\frac{P_{sm}}{P_0} = \sum_i N_i\cdot K^2{}_i\cdot\frac{P_{si}}{P_0}\le\left(\frac{1}{10}\right)^2$$
.

It can be seen that each noise path contributes a fraction of the noise power

$$F_i = \frac{N_i\cdot(K_i)^2\cdot P_{si}/P_0}{\sum N_i\cdot(K_i)^2\cdot P_{si}/P_0} = \frac{N_i\cdot(K_i)^2\cdot(P_{si}/P_0)_{REQ}}{\left(\frac{1}{10}\right)^2} .$$

Then the noise budget will be optimally used if each scattered light path is allocated part of the total noise budget in proportion to the noise allocation factor F_i for the particular scattering path. This allocation also ensures that the individual scattered light noise requirements add up to the specified total.

$$\left(\frac{is_i}{i_{gSRD}}\right)^2\le F_i\cdot\left(\frac{1}{10}\right)^2 .$$

7.6. Scattered Light Power Ratio Requirement

The scattered light power ratio requirement for a particular scattering path is given by

$\left(\frac{P_{si}}{P_0}\right)_{REQ}\le\frac{F_i}{N_i\cdot K_i^2}\cdot\left(\frac{1}{10}\right)^2$, where

N_i and F_i are estimated from the scattered light calculations presented in the Core Optics Support Conceptual Design, LIGO-T970072-00-D, and the K_i are presented below.

7.6.1. K_i Values

The K_i values for the vacuum mounted surfaces were taken from Secondary Light Noise Sources in LIGO, LIGO-T970074-00-D. They scale with frequency as follow, where x_{vh} is the amplitude spectral density of the scattering surface in m/root Hz, and X is the gravity wave amplitude sensitivity spectral density of the initial LIGO in m/root Hz.

$$K_{ITM} = \frac{1 \cdot 10^{-19}}{X(f)} \cdot \frac{x_{vh}(f)}{1 \cdot 10^{-11}} \cdot 3 \cdot 10^5$$

$$K_{DPS} = \frac{1 \cdot 10^{-19}}{X(f)} \cdot \frac{x_{vh}(f)}{1 \cdot 10^{-11}} \cdot 3 \cdot 10^5$$

$$K_{ETM} = \frac{1 \cdot 10^{-19}}{X(f)} \cdot \frac{x_{vh}(f)}{1 \cdot 10^{-11}} \cdot 2 \cdot 10^4$$

The K_{SPS} value for light scattered from the SPS beam into the recycling cavity is given by

$$K_{RPS} = \frac{1 \cdot 10^{-19}}{X(f)} \cdot \frac{x_{vh}(f)}{1 \cdot 10^{-11}} \cdot 1 \cdot 10^4 \quad .$$

7.6.2. Summary of Ki values in frequency band 30 - 1000 Hz

Table 11: Scattered Light Phase Noise Current Transfer Coefficient (K_i) for Scattering from Surfaces Mounted on Vacuum Housing and SEI Platform, for Initial LIGO Sensitivity

Surface Mount	*Scattering Path*	K_i @ 30Hz	K_i @ 100Hz	K_i @ 1000Hz
Vacuum housing	ITM PO to window on vac housing into recycling cavity	3×10^5	3×10^5	6×10^2
	ITM/ETM diffuse scatter into arm cavity	4.5×10^6	4.5×10^6	8.9×10^3
	APS to window on vac housing onto BS	3×10^5	3×10^5	6×10^2
	ETM PO to window on vac housing into arm cavity	2×10^4	2×10^4	40
	SPS from vac housing into recycling cavity	1×10^4	1×10^4	18
SEI	ITM GB and BS GB to beam-dump on SEI into recycling cavity	300	50	0.3

APPENDIX 3

8 GHOST BEAM GLINT CALCULATIONS

The criterion for determining which ghost beams must be dumped will be that an *un-dumped* ghost beam which reflects from the wall of the vacuum housing and causes a direct glint into the IFO shall not cause excessive phase noise. The worst case estimate would result from a cylindrical surface aligned exactly perpendicular to the ghost beam direction, as shown in the figure 13 (note: the surface can be either convex or concave). An example of such a glint surface might be the inner wall of the BSC housing.

The ghost beam glint from the reflecting surface will retroreflect into the solid angle of the IFO provided the tilt of the curved surface is within the diffraction angle of the IFO beam. The maximum illuminated area of the glint surface which meets these conditions is

$$A_g = R\theta_d w = R \cdot \left(\frac{2}{\pi} \cdot \frac{\lambda}{w}\right) \cdot w = \frac{2}{\pi} R\lambda \quad .$$

The retroreflected light from the glint into the IFO is proportional to the incident power, to the ratio of glint area to ghost beam area, and to the return transmissivity through the COC.

$$P_g = P_i \cdot \frac{2R\lambda}{\pi^2 w^2} \cdot T \quad .$$

The width of the glint surface is

$$l = \frac{2}{\pi} \cdot \frac{R\lambda}{w},$$

and the geometric optics approximation is valid for $l \gg \lambda$. For the LIGO IFO parameters, the approximation is valid for $R > 0.4m$

We will estimate the glint power assuming a radius of R=1.5m, which corresponds to the inside walls of the BSC chamber, and the following parameters:

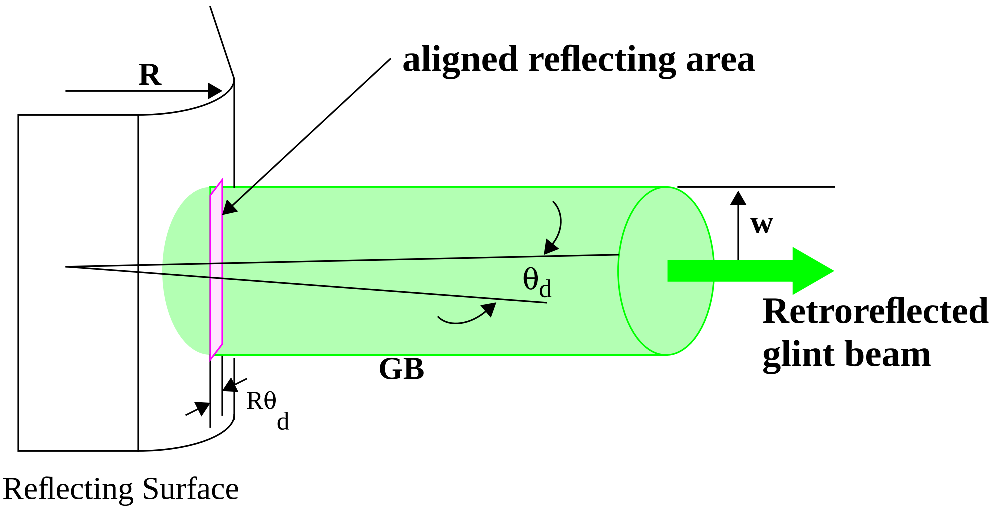


Figure 13: Glint Reflection of GBAR$_3$ Back Into the IFO

w=0.0364 m

$\theta_d = 9.3 \times 10^{-6}$ rad.

A summary of the scattered light from the first two orders of ghost beams is shown in Table 7, “Summary of Ghost Beam Scattered Light Powers,” on page 17. The third column of numbers lists the scattered light power with GB1, GB3 and selected GB4 beams being dumped onto beam-dump apparati mounted to the vacuum housing. The glint power was calculated for each GB4 beam, assuming that the GB4 beams were *not* dumped; and is presented in the fourth column of numbers, together with the corresponding rms amplitude noise/signal ratio in the fifth column. It can be seen from the table that the ITMxGBAR4, ITMyGBAR4, BSGBAR4x, BSGBHR4x, ITMxGBHR4, and ITMyGBHR4 beams *may* cause a glint into the IFO which exceeds the scattered light noise requirement, and therefore must be dumped. The fifth column lists the corresponding rms amplitude noise/signal ratio which results if the GB4 beams are not dumped.

Therefore, all GB1, and GB3 beams from the BS, ITM, and ETM shall be dumped. In addition the following GB4 beams shall be dumped: ITMxGBAR4, ITMyGBAR4, BSGBAR4x, BSGBHR4x, ITMxGBHR4, and ITMyGBHR4.