LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- 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, RPS beam, DPS 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 RPS 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
- 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
- DPS - Dark (antisymmetric) port signal
- RPS - Reflected (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 |

**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

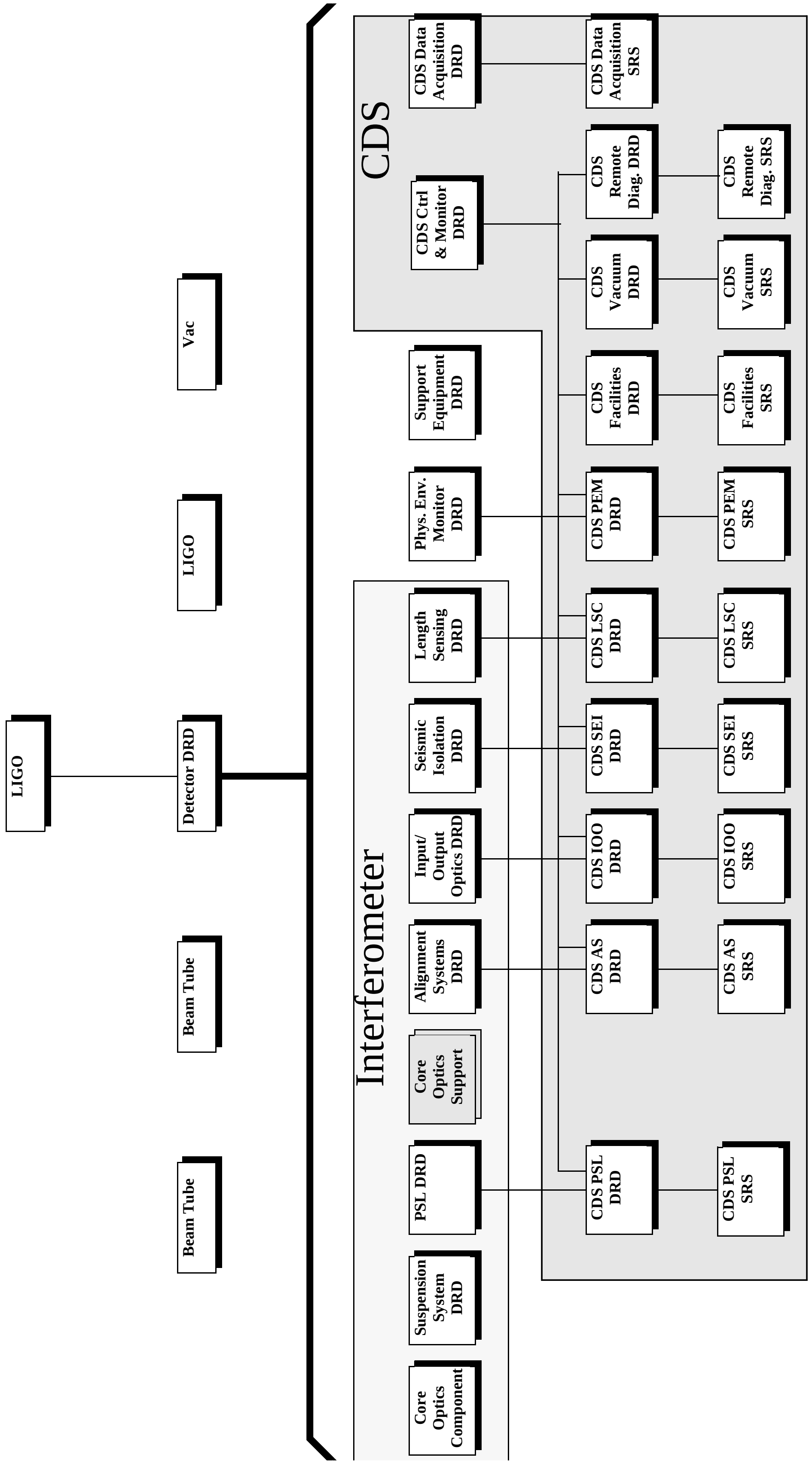
2) Note on Scattering in the Interferometer: ~jordan/cos/T970083-00-D.fm

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

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

## 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 surrounding the COC and IOO to control or reduce the energy level of the intra-cavity scattered light.

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.

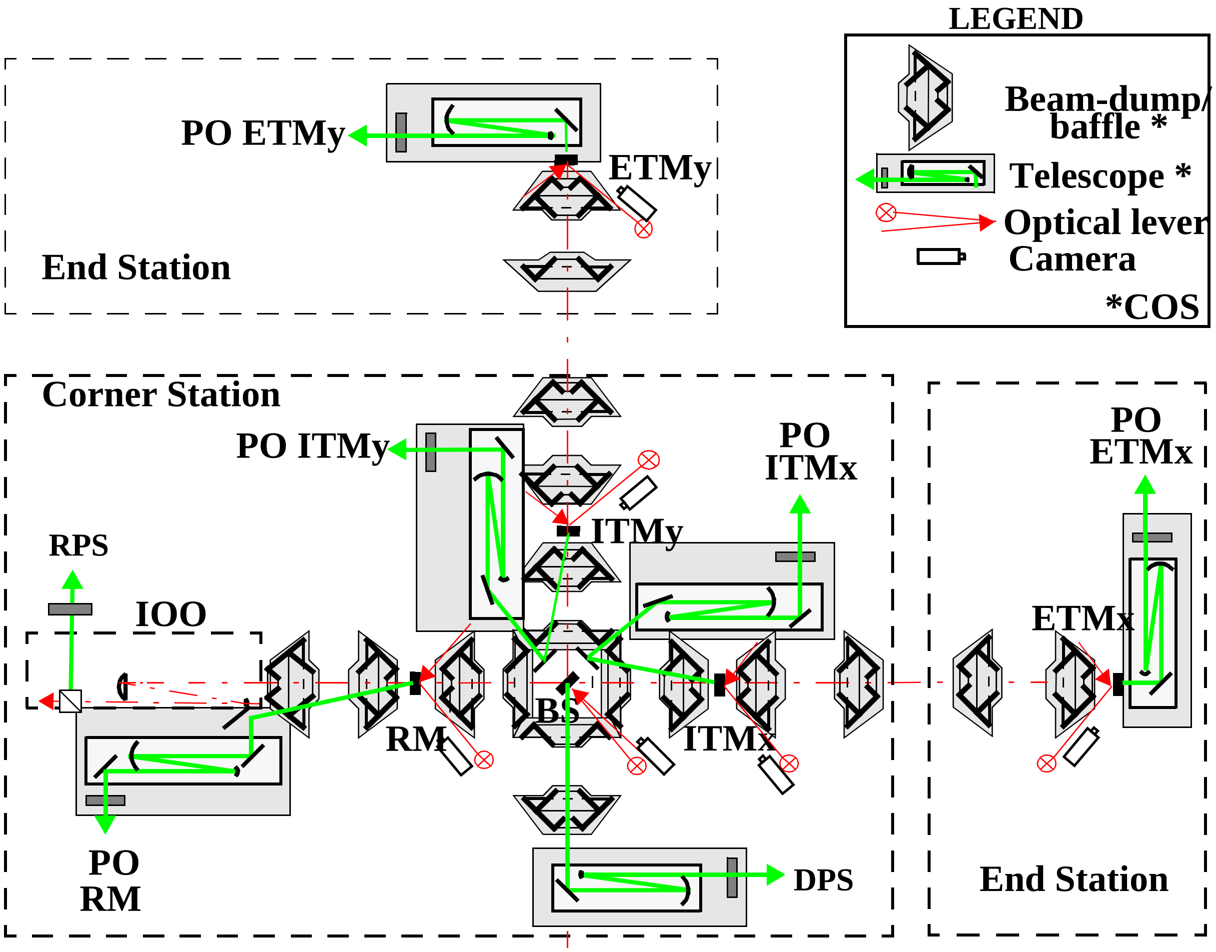


Figure 1: Core Optics Support Subsystem Elements, 4K IFO- Schematic Layout

### 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... |

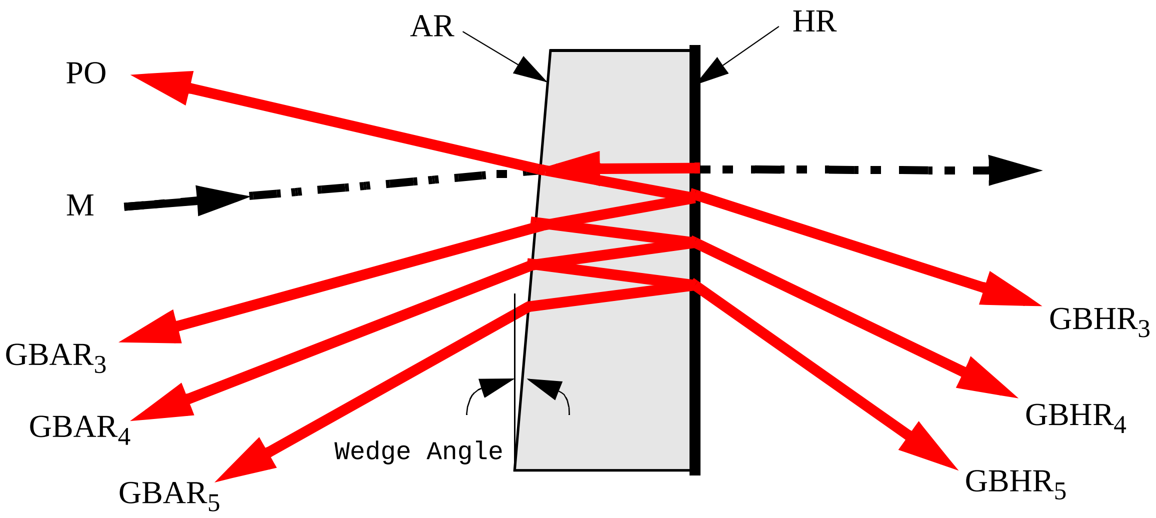


**Figure 2: Optical Beam Designation**

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

The first surface reflection from the AR surface of the RM and both ITM mirrors, the ETM output beams, the DPS beam, and the RPS beam will be delivered outside the vacuum housing to the ASC/LSC.

### 2.2.3. COC Ghost Beam Control

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

### 2.2.4. Diffuse Scattered Light Control

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

### 2.2.5. Delivery Optics for PO Beams, DPS Beam, and RPS Beam

Beam Reducing Telescopes and turning mirrors will be provided to reduce the size of the PO beams, the DPS beam, and the RPS beam, and to direct these beams through the optical windows of the vacuum housings to the ASC/LSC subsystems.

## 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 | <0.001 | <0.0004 | <0.0004 | <0.001 | <0.001 |
| substrate thickness, cm | 10 | 4 | 10 | 10 | 10 |
| mirror reflectivity | .97 | .5 | .97 | .97 | .99998 |
| refractive index @ 1.06 | 1.45 | 1.45 | 1.45 | 1.45 | 1.4 |
| 100ppm power contour radius, cm | 7.8 | 7.8 | 7.8 | 7.8 | 9.8 |
| 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. ASC/LSC Interface Characteristics

#### 2.4.2.1 ASC/LSC Sensor Beam Parameters

The COS pick-off beam characteristics will be compatible with the ASC 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 | > 9.8 mm |
| wave front distortion | < $\lambda/4$ p-v, See “PO Wavefront Distortion Requirement” on page 22. |
| 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 |

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

| *Physical Quantity* | *Characteristic* |
|---|---|
| beam orientation | nominally horizontal, and perpendicular to IFO axis |
| beam polarization | vertical |

### 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*

- T*he requirement for the COS will be that 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 $Q$s 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 DPS beam which is backscattered from the output window and the optical surfaces in the ASC/LSC subsystems back onto the BS, 2) the two ITM PO beams which backscatter from the output window mounted on the vacuum housing and the optical surfaces in the ADC/LSC into the recycling cavity, and 2) 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 five scattered light noise sources account for over 99% 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 $\theta_{iwo}$ 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, if the beam diameter has been demagnified from the original IFO diameter by the output telescope. 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 square of the demagnification.

The scattered light requirements are allocated to the various scattering paths proportionally to the relative magnitudes of the particular paths. See “Basis for Noise Calculations” on page 22.

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

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

**Table 5: 4K IFO Scattered Light Requirements @ 100 Hz, $P_{laser}$=6w, $G_{rc}$=50, M=1/72.**

| *Scattering path* | *Power incident on surface, $P_i$, watt* | *Noise allocation factor* | *Scattered light requirement, $(P_s)_{REQ}$, watt* | *Attenuation of scattered light path* | *Implied BRDF of all surfaces in demagnified output beam, $sr^{-1}$* |
|---|---|---|---|---|---|
| $P_{\text{DPS-vh-BS}}$ | 0.30 | 0.30 | $<2.0\times10^{-13}$ | $A_{FI} = 0.001$ | $8\times10^{-4} sr^{-1}$ |
| $P_{\text{ITMPO-vh-ITM}}$ | 0.15 | 0.27 | $<1.8\times10^{-13}$ | $R_{ITM} = 1\times10^{-3}$ | $8\times10^{-4} sr^{-1}$ |
| $P_{\text{ETMPO-vh-ETM}}$ | 0.39 | 0.08 | $<1.2\times10^{-11}$ | $T^2_{ND}= 0.04$ | $8\times10^{-4} sr^{-1}$ |

### 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 Beam-dumps and Baffling of Main Beam Optics, Requirements

#### *3.1.1.3.1 General*

- Beam-dumps shall attenuate the scattered light from PO and ghost beams to acceptable levels (See “Scattered Light” on page 10.).
- Baffles shall not interfere with the passage of PO beams.
- The baffles will be mounted on an SEI optical platform wherever possible and shall not interfere with the COC mounting suspensions.
- The baffles shall be composed of vacuum compatible materials. (See LIGO Vacuum Compatibility, Cleaning Methods and Procedures, LIGO-E960022-00-D)
- The baffles shall allow sufficient access for an optical lever beam and for TV camera viewing of the COC mirror surface (see ASC Optical Lever Design Requirement Document, LIGO-T950106-01-D).

A typical design concept for the ITMx ghost beams is shown in figure 3. Beam-dumps are located next to the COC on both sides to attenuate $GBAR_5$, $GBHR_5$ and higher angle beams; and at the adjacent platform to attenuate $GBAR_3$, $GBHR_3$, $GBAR_4$, and $GBHR_4$.

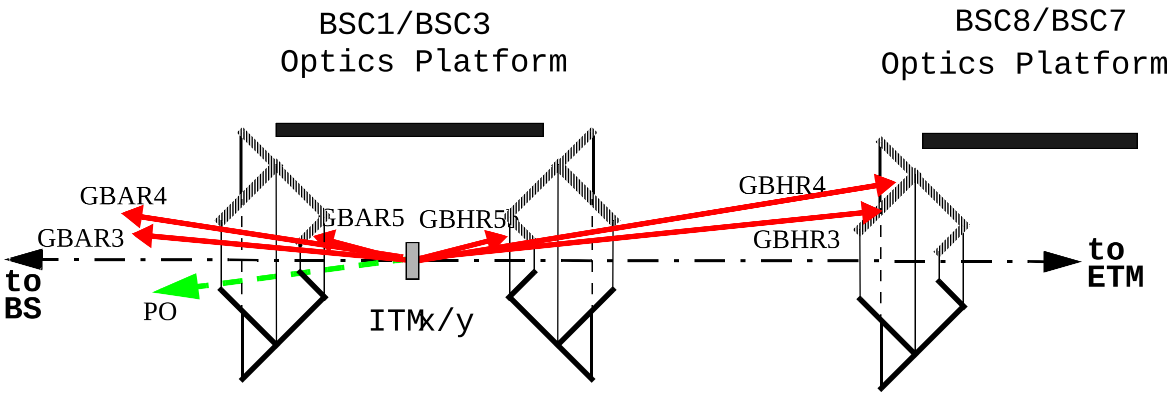


Figure 3: Typical Design Concept for Beam-dump/baffle

### 3.1.1.4 Baffling of Support Optics

#### *3.1.1.4.1 IOO beam-dump/baffle*

A beam-dump/baffle shall be placed at the output of the IOO telescope to block all off-axis rays entering the RM aperture to acceptable levels.

All baffling internal to the IOO subsystem will be provided by IOO.

### 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.

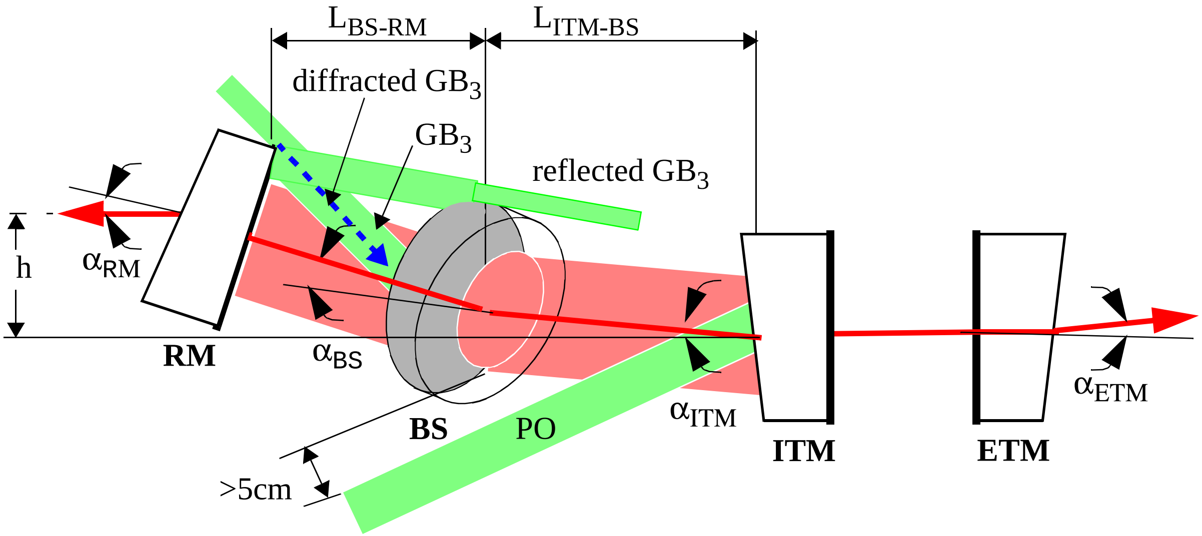


Figure 4: Separation of ITM PO and BS GB Beams caused by the COC Wedge Angles

### 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 4.

*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 6 on page 14 and Table 7 on page 14 for the 4K and 2K IFO respectively. See Determination of the Wedge Angles for the Core Optics Components, T970091-00-D

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**Table 6: 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′ ± 5′ | –1.083° | 8.7 cm | 2.0 m | 7.1 cm |
| BS | 1° ± 5′ | 0.558° | 4.4 cm | 4.8 m | 8.6cm |
| ITM | 1°10′ ± 5′ | 0.525° | 0.0 cm | 4.8 m | 10.9 cm |
| ETM | 2° ± 5′ | 0.899° | 0.0 cm | 2.0 m | 2.9 cm |

**Table 7: 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′ ± 5′ | –1.083° | 14.7 cm | 2.8 m | 16.9 cm |
| BS | 1° ± 5′ | 0.558° | 8.7 cm | 3.0 m | -12.8 cm (see note below) |
| FM |  | 0.269° | 0.2 |  |  |
| ITM | 34′ ± 5′ | 0.255° | 0.0 cm | 9.3 m | 9.3 cm |
| ETM | 2° ± 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 delivered beam diameter will be determined by a beam-reducing telescope mounted on the appropriate optics platform within the vacuum enclosure.

The COS PO beams will comprise the first surface reflections from the antireflection (AR) coated sides of the RM, ITMx and ITMy; the directly transmitted beams through the AR side of $ETM_x$ and $ETM_y$; and the DPS beam exiting the dark port.

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**Table 8: Requirements for PO Beam Reducing Telescope**

| *Property* | *Value* | | *Comment* |
|---|---|---|---|
| | *RM, ITM, DPS* | *ETM* | |
| configuration | off-axis parabolic | off-axis spherical | • |
| total curvature and astigmatism aberration[a] | <λ/4 peak-valley @ λ=1.06 micron | <5λ peak-valley @ λ=1.06 micron | *RM, ITM, DPS*: $TEM_{00}$-$TEM_{01}$ Guoy phase uncertainty <10 deg |
| total higher order aberrations[b] | <λ/20 peak-valley @ λ=1.06 micron | <1λ peak-valley @ λ=1.06 micron | *RM, ITM, DPS*: $TEM_{00}$-$TEM_{01}$ Guoy phase uncertainty <10 deg |
| input clear aperture diameter | 156 mm | 156 mm | • RM, ITM, DPS:@100 ppm beam power diameter<br>• ETM:@ 3000ppm |
| output clear aperture diameter | 15.6 mm | 15.6 mm | compatible with ASC input requirements |
| Internal resonance and Q | TBD | TBD | |
| output beam parameter | 3.64 mm | 3.64 mm | |
| output beam waist location | TBD | TBD | compatible with ASC input requirements |
| magnification | 0.1X | 0.1X | |

[a] based on a private communication from Daniel Sigg regarding an estimate of the ASC signal loss with a λ/4 peak-valley wavefront aberration @ λ=1.06 micron

[b] same as above

### 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 ASC/LSC subsystems.

The scattering requirement for the two surfaces of the output window is relaxed from the requirement for the BRDF of all surfaces in the DPS output beam by the factor $(7.2)^2=52$, because the output beam through the window has only been demagnified by 1/10, and not by 1/72.

The surface figure of the window will cause an optical path difference (OPD) aberration of the beam wavefront. The total OPD for both surfaces is

$OPD = 2 \cdot (1-n) \cdot \Delta t$ , where n is the index of refraction and $\Delta t$ is the deviation from flatness of the surface.

For a p-v surface deformation of

$\Delta t = \frac{\lambda}{20}$ ‘

the window will add an aberration of

$OPD = 0.045\lambda$, which will increase the wavefront aberration from $0.25\lambda$ to $0.30\lambda$. This may be acceptable to WFS.

The specifications for the PO windows are summarized below.

**Table 9: Requirements for PO Beam Vacuum Window**

| *Property* | *Value* |
|---|---|
| material | fused silica |
| thickness | TBD |
| substrate diameter | TBD |
| wedge | $34° \pm 5'$ |
| clear aperture | >20 mm |
| surface figure | $\lambda$/20 per surface over clear aperture |
| AR coating, both surfaces | <.001 @1064 nm, @ $55.4°$ incidence angle, p polarization |
| $\mathrm{BRDF}_{wo}$ | $< 5\mathrm{x}\ 10^{-2}\ \mathrm{sr}^{-1}$ |
| Vacuum properties | Vacuum Equipment Specification, LIGO-E940002-02-V |

#### 3.1.1.9 Beam-dump surface scattering requirements

The requirement for the PO beam scattered power from a surface mounted on the SEI platform into the recycling cavity (Table 5, “4K IFO Scattered Light Requirements @ 100 Hz, Plaser=6w, Grc=50, M=1/72.,” on page 11) places an *implied* requirement (See “Beam-dump surface scattering requirement” on page 31.) on the $BRDF_{bd}$ of the beam-dump surface

- $BRDF_{bd} < 2\pi\, sr^{-1}$.

### 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 Initial Optical Alignment of IFO

The COS optical beam-dump/baffles shall be compatible with the initial optical alignment of the IFO.

#### 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. 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* ASC/LSC *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 ASC/LSC 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 > 78 mm in the primary beam and > 7.8 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 LIGO Project System Safety Management Plan 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.

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

$u_0$ 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 Wavefront Distortion Requirement

The PO beam reducing telescope, the optical output window, and all other COS optical elements shall not aberrate the wavefront of the PO beam by more than λ/4. This amount of aberration will result in < 10% loss in ASC signal, and is acceptable[1] to the ASC subsystem.

# 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 23; and on the estimate of scattered light intensities from various scattering sources in the IFO, as calculated in Core Optics Support Conceptual Design, LIGO-T970072-00-D

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[1] private communication, Daniel Sigg

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**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

### 7.2.1. DPS beam scattering requirement

The DPS beam is scattered by the output surfaces mounted on the vacuum housing, as shown schematically in figure 5. *Note that a Faraday isolator has been included to reduce the backscattered light to acceptable levels*.

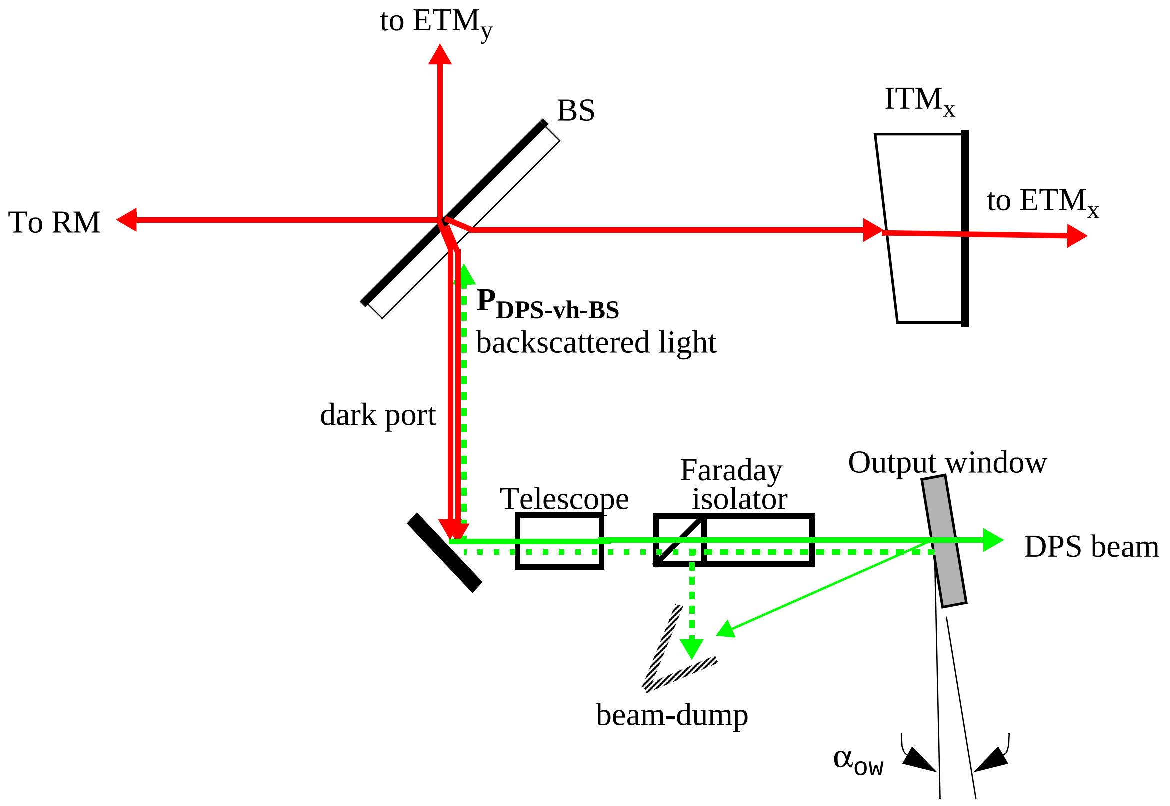

Figure 5: The Scattered DPS Beam from the Output Window Mounted on the Vacuum Housing

The backscattered power of the DPS beam ($Ps_{DPS}$) from all output surfaces relative to the input laser power ($P_0$) is given by

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

, where

| | |
|---|---|
| transmissivity of BS AR coating, | $T_{BSAR} = 0.9996$ |
| output window incidence angle | $\theta_{iwo} = 57$ deg |
| magnification of the telescope | $M = 0.01389$ |
| power attenuation factor of the Faraday isolator | $A_{Fi} = 0.001$, |
| ratio of the DPS signal to the input laser power, | $P_{DPS}/P_0 = 0.05$ |
| laser wavelength | $\lambda = 1.06\times10^{-6}$ m |
| Gaussian beam parameter | $w_0 = 0.0364$ m. |

See “Core Optics Parameters” on page 9.

The scattering acceptance cone will be taken to be the 1/e solid angle which contains 86% of the IFO Gaussian beam power

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

The relative noise amplitude is given by

$$\frac{i_{sDPS}}{i_{gSRD}} = K_{DPS} \cdot \sqrt{\frac{P_{sDPS}}{P_0}} ,$$

where

$i_{sDPS}$ is the photocurrent at the detector vibration frequency due to scattered light
$i_{gSRD}$ is the photocurrent for the gravitational wave strain at the initial LIGO sensitivity,
$P_{sDPS}$ is the scattered light power out the dark port (antisymmetric),
$P_0$ is the laser power into the RM,
$K_{DPS}$ is the proportionality factor between the photocurrent noise ratio and the root scattered light power ratio.
$K_{DPS} = 3\times10^5$

The maximum *implied* $BRDF_{DPS}$ is calculated with a Faraday isolator in the output path, assuming that the DPS scattered light power does not exceed the scattering requirement below(See “4K IFO Scattered Light Requirements @ 100 Hz, Plaser=6w, Grc=50, M=1/72.” on page 11.)

$$(P_{sDPS})_{REQ} \le 2.0\times10^{-13}$$

- Then the *implied* requirement for the combined DPS output scattering surfaces in the demagnified beam is:
  $BRDF_{DPS} < 8\text{x}10^{-4}\ sr^{-1}$, *with a Faraday isolator.*

### 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 6.

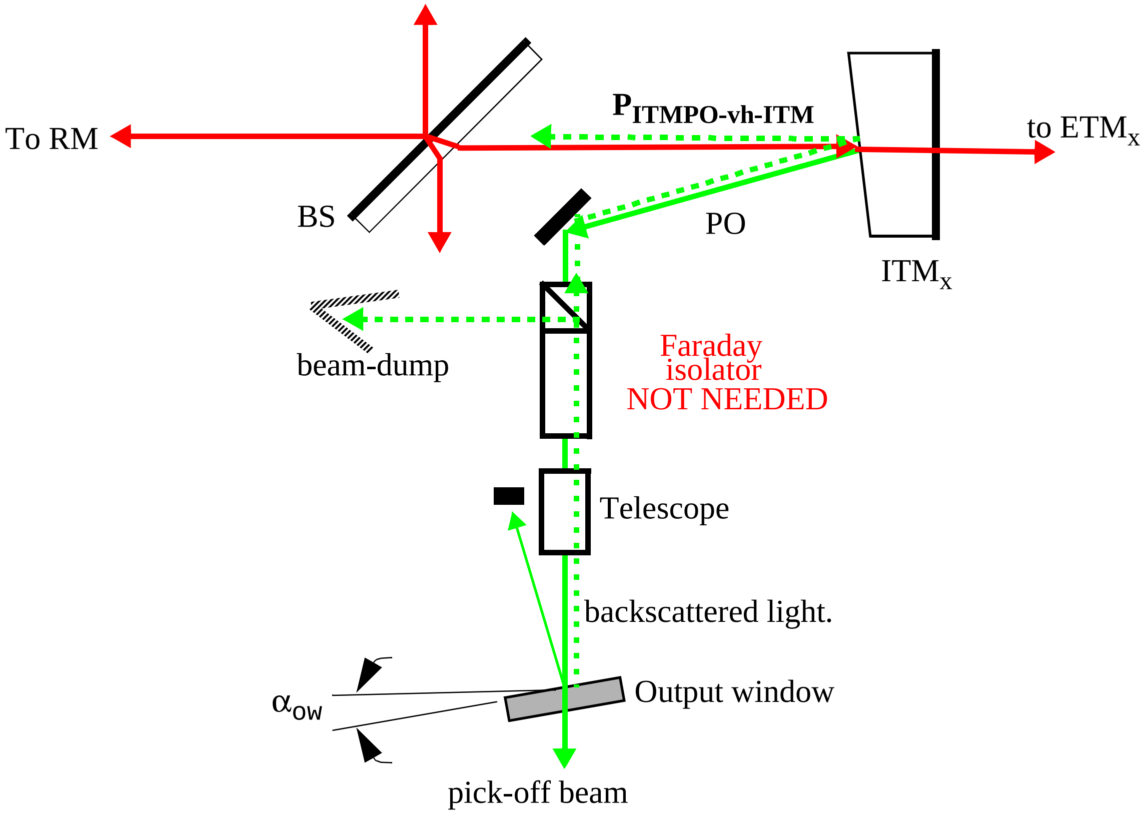

**Figure 6: Backscattered light from $ITM_x$ PO and $ITM_y$ PO beams injects noise into the recycling cavity.**

Note that the output window must be tipped in order to catch the specular back-reflected beam from the parallel AR surfaces of the window. A Faraday isolator may not be needed to reduce the backscattered light.

The relative backscattered intensities of each ITM PO beam from the output surfaces mounted on the vacuum housing into the recycling cavity is given by

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

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

| | |
|---|---|
| output window incidence angle | $\theta_{iwo} = 57$ 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 | $G_{rc} = 60$ |
| attenuation factor of the Faraday isolator | $A_{Fi} = 1$ (not needed in this case) |

The relative noise amplitude is given by

$$\frac{i_{sITM}}{i_{gSRD}} = K_{ITM} \cdot \sqrt{\frac{P_{sITM}}{P_0}}$$ , where

$K_{ITM} = 5 \times 10^5$. See Secondary Light Noise Sources in LIGO, LIGO-T970074-00-D

The maximum *implied* $\mathrm{BRDF}_{\mathrm{wo}}$ is calculated assuming that the ITM PO scattered light does not exceed the scattering requirement (Table 5, “4K IFO Scattered Light Requirements @ 100 Hz, Plaser=6w, Grc=50, M=1/72.,” on page 11)

$(P_{sITM})_{REQ} \le 1.8 \times 10^{-13}$

- Then the *implied* requirement for the combined ITM PO output surfaces in the demagnified beam is:
  $\mathrm{BRDF}_{\mathrm{ITM\ PO}} < 8\mathrm{x}10^{-4}\ \mathrm{sr}^{-1}$, *without a Faraday isolator*.

## 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 Figure7

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

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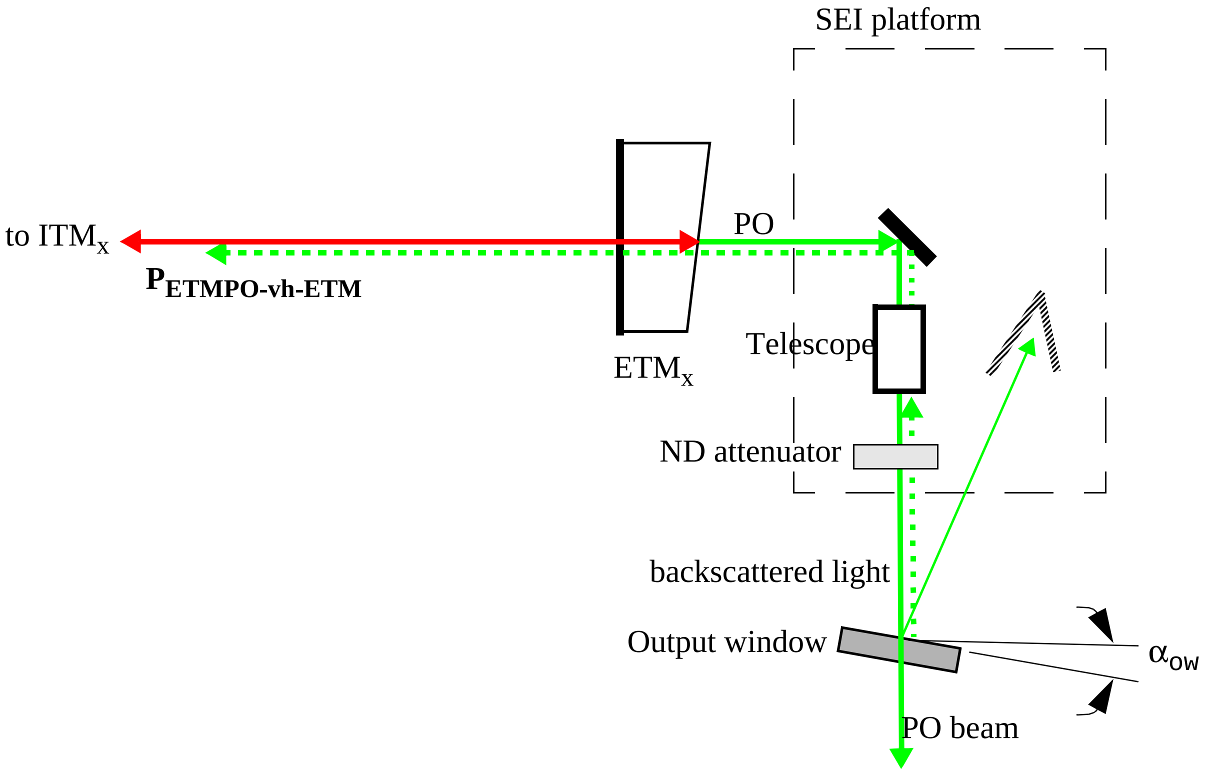

Figure 7: ETM PO beam backscattered into arm cavity from output window mounted on vacuum housing

The relative backscattered intensities of each ETM PO beam from the output surfaces mounted on the vacuum housing into the recycling cavity is given by

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

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

$T_{ETMAR} = 0.999$
$T_{ETMHR} = 0.000020$
$R_{ETMHR} = .999980$
$R_{ITMHR} = .97$
$G_{rc} = 50$
$\theta_{iwo} = 57$ deg
$M = 0.01389$

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

transmissivity of the Fabry-Perot arm cavity at resonance is

$$T_{FP} = \frac{(\qquad\qquad)\cdot(\qquad\qquad)}{(\quad\sqrt{\qquad\qquad\qquad})} = 0.0026$$

transmissivity of neutral density filter

$T_{ND} = 0.20$

The maximum *implied* BRDF$_{\text{ETM PO}}$ is calculated assuming that the ETM PO scattered light does not exceed the scattering requirement (See “4K IFO Scattered Light Requirements @ 100 Hz, Plaser=6w, Grc=50, M=1/72.” on page 11.)

$(P_{sETM})_{REQ} \leq 1.2\times10^{-13}$

- The *implied* requirement for the combined ETM output surfaces in the demagnified beam is: BRDF$_{\text{ETM PO}} < 8\text{x}10^{-4}$ sr$^{-1}$.

### 7.2.4. RPS beam scattering requirement

The RPS beam will scatter from the surfaces of the output window and inject noise into the recycling cavity through the RM, as shown in figure 8.

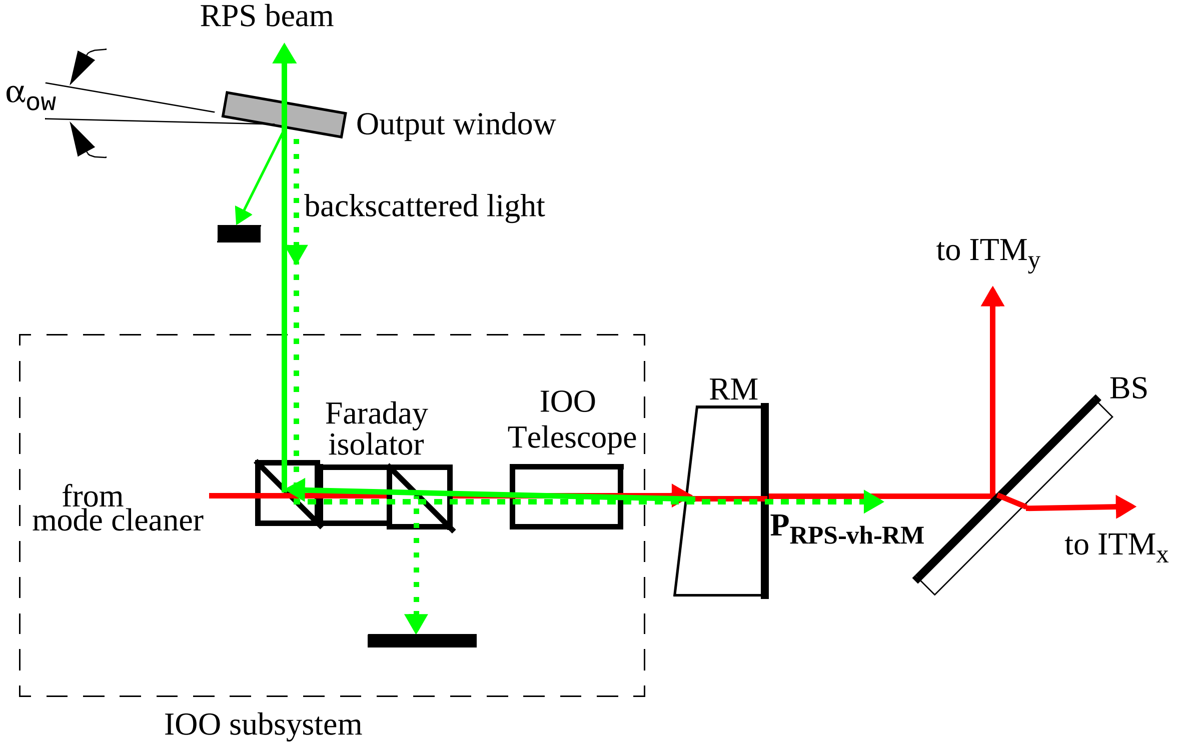

**Figure 8: RM RPS beam backscattered into recycling cavity from output window mounted on vacuum housing**

The relative backscattered intensities of the RPS beam from the output surfaces mounted on the vacuum housing into the recycling cavity is given by

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

ratio of the RPS signal to the input laser power, $\frac{P_{RPS}}{P_0} = 0.02$
$A_{Fi} = 0.001$
$T_{RMAR} = 0.999$
$T_{RMHR} = 0.03$
$\theta_{iwo} = 57$ deg
$M = 0.05$
$\Delta\Omega = 2.7\times10^{-10}\ sr^{-1}$.

The maximum *implied* $BRDF_{wo}$ is calculated, assuming that the RPS scattered light does not exceed the scattering requirement (See “4K IFO Scattered Light Requirements @ 100 Hz, Plaser=6w, Grc=50, M=1/72.” on page 11.)

$(P_{sRPS})_{REQ} \leq 1.0\times10^{-13}$

- The *implied* requirement for the combined RPS output surfaces in the demagnified beam is: $BRDF_{RPSwo} < 8\times10^{-4}\ sr^{-1}$.

### 7.2.5. RM PO beam scattering requirement

The RM PO beam backscatters and reflects from the AR coating of the RM, through the IOO telescope, and through two Faraday isolators before entering the laser cavity. Assuming an RM AR coating reflectivity of $10^{-3}$, a Faraday isolator field attenuation of $10^{-3}$, and a *BRDF of* $10^{-3}$*;* a fraction $10^{-18}$ of the incident laser power will be backscattered into the laser. *Therefore, the RM PO scattered light will be ignored in comparison with the backscattering from other IOO optical elements.*

## 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 23.). 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 $3\times10^{-5}$ smaller than the vacuum housing displacement (See “Noise Amplitude Parameters in the Frequency Range 30<f<1000 Hz” on page 23.).

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 power requirement for scattering from SEI mounted surfaces is*

*$10^{-10}$ times smaller than the requirement for scattering from vacuum housing mounted surfaces and can be ignored*.

### 7.3.1. Beam-dump surface scattering requirement

Backscattering from the beam dump may be neglected for the following reasons. The path to the beam dump involves ghost beams which are down from the main beam intensity by a factor of at least $10^{-3}$, the AR reflectivity. Thus their maximum intensities are of the order of the ITM pick-off beam intensity. However the amplitude of the seismic motion of the beam dump is down by a factor ~$10^{-4}$ compared to the seismic motion of the ITM pick-off beam scattering surfaces. Thus the required BRDF of the beam dump is of order $(\quad)^2 \times 10^{-3}$. This number is so large compared to unity that any beam dump surface backscattering can be neglected. A reasonable value for the BRDF of the beam dump material is $10^{-3}$.

## 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 23). 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.*

Diffuse light scattered from the COC, not in a specular ghost beam path, which backscatters from a baffle surface mounted to the vacuum housing, must make one additional diffuse backscatter from a COC into the acceptance solid angle of the cavity in order to be injected into the main IFO beam. Assuming $BRDF_{COC} = 3\times10 \ sr^{-1}$ @ $1^{o}$ incidence angle (see Basis of the Optical Wavefront Specifications, LIGO-T952009-00-R, Basis of the Optical Wavefront Specifications, LIGO-T952009-00-R), $BRDF_b = 3\times10 \ sr^{-1}$, and $\Delta\Omega = 2.7\times10 \ sr$ ; the fraction of the light scattered from the COC which injects into the IFO cavity will be at least a factor $10^{-14}$ smaller than that which backscatters from a PO beam.

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

## 7.5. Summary of Scattered Light Requirements

The estimated relative scattered powers (see Core Optics Support Conceptual Design, LIGO-T970072-00-D document), the scattered light requirements, and the implied BRDF requirements for the scattering surfaces for the significant noise sources, are listed in Table 5 on page 11; **with**

**M=0.01389, and $A_{Fi}$=0.001**. The scattered light requirements at 1000 Hz are relaxed by the factor 0.002 because of the reduced displacement amplitude of the scattering surfaces.

## 7.6. Noise Allocation Factor

The noise/signal power ratio for a given scattering path is described by the following relationship (See Secondary Light Noise Sources in LIGO, LIGO-T970074-00-D.)

$$\left( \quad \right)^2 = K_i^2 \cdot \frac{P_{si}}{P_0}, \text{ and}$$

$$\left( \quad \right)^2 = N_1 \cdot \quad \cdot \frac{P_{s1}}{P_0} + N_2 \cdot \quad \cdot \frac{P_{s2}}{P_0} + \quad + N_m \cdot \quad \cdot \frac{P_{sm}}{P_0} = \sum_i N_i \cdot \quad \cdot \frac{P_{si}}{P_0} \le \left( \quad \right)^2 .$$

Each noise path contributes a fraction of the noise

$$F_i = \frac{N_i \cdot (\quad)^2 \cdot P_{si}/P_0}{\sum N_i \cdot (\quad)^2 \cdot P_{si}/P_0} .$$

Then the noise budget will be used optimally 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.

$$\left( \quad \right)^2 \le F_i \cdot \left( \quad \right)^2 .$$

## 7.7. Scattered Light Power Ratio Requirement

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

$$\left( \quad \right)_{REQ} \le \frac{F_i}{N_i \cdot K_i^2} \cdot \left( \quad \right)^2, \text{ where}$$

$N_i$ 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.

### 7.7.1. $K_i$ 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 follows.

$$K_{ITM} = \frac{1 \cdot 10^{-19}}{x(\ )} \cdot \frac{x(\ )}{1 \cdot 10} \cdot 3 \cdot 10^5$$

$$K_{DPS} = \frac{1 \cdot 10^{-19}}{x(\ )} \cdot \frac{x(\ )}{1 \cdot 10} \cdot \quad \cdot 10^5$$

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

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

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

### 7.7.2. 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 | $3 \times 10^5$ | $3 \times 10^5$ | $6 \times 10^2$ |
| | DPS to window on vac housing onto BS | $3 \times 10^5$ | $3 \times 10^5$ | $6 \times 10^2$ |
| | ETM PO to window on vac housing into arm cavity | $2 \times 10^4$ | $2 \times 10^4$ | 40 |
| | RPS from vac housing into recycling cavity | $1 \times 10^4$ | $1 \times 10^4$ | 18 |
| SEI | ITM GB and BS GB to beam-dump on SEI into recycling cavity | 300 | 50 | 0.3 |

### 7.7.3. Scattered Light Power Requirement

The noise allocation factors and the effective number of beams 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 following parameters were assumed.

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

$$\frac{P_{DPS}}{P_0} = 0.05$$

$$\frac{P_{RPS}}{P_0} = 0.02$$

The scattered light requirements were then calculated from the following equation:

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

The scattering requirements for the 4K and 2K IFO are shown in the following table (See “Scattered Light Requirements for Significant Noise Paths- 4K IFO and 2K IFO” on page 34.).

**Table 12: Scattered Light Requirements for Significant Noise Paths- 4K IFO and 2K IFO**

| *noise path* | *effective no. of beams* | *noise allocation factor* | *scattering requirement per source* $P_{si}$ | | |
|---|---|---|---|---|---|
| | | | *30 Hz* | *100 Hz* | *1000Hz* |
| $P_{DPS\text{-}vh\text{-}BS}$ | 1 | 0.30 | $<2.0\times10^{-13}$ | $<2.0\times10^{-13}$ | $< 4.9\text{x}10^{-8}$ |
| $P_{ITMPO\text{-}vh\text{-}ITM}$ | 2 | 0.27 | $<1.8\times10^{-13}$ | $<1.8\times10^{-13}$ | $< 4.5\text{x}10^{-8}$ |
| $P_{ETM\text{-}vh\text{-}ETM}$ | 2 | 0.08 | $<1.2\times10^{-11}$ | $<1.2\times10^{-11}$ | $< 3.1\text{x}10^{-6}$ |