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40m Optical Systems and Sensing
Design Requirements Document & Conceptual Design

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LIGO Science Collaboration

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1 Introduction

1.1 Purpose

The purpose of this document is to describe the design requirements for the Optical Systems and ISC. Primary requirements are derived (“flowed-down”) from the Conceptual Design of the 40 Meter Laboratory Upgrade for Prototyping an Advanced LIGO Interferometer, LIGO-T010029.

1.2 Scope

The Optical Systems and Sensing is divided into three distinct subsystems: Interferometer Input Beam, Sensing Beams, and Viewports. The Interferometer Input Beam is comprised of the following elements: Input Monitor, IMC Mode Matching Optics, IMC Beam Steering, Input Mode Cleaner (IMC), Input Faraday Isolator, IFO Mode Matching Telescope, IFO Beam Steering. The Sensing Beams is comprised of the following elements: Initial Pointing Beam, IMC Reflected Beam, IMC Transmitted Beam Symmetric Port Signal, ITMx Pickoff Beam, ITMy Pickoff Beam, BS Pickoff Beam, AP1 Output beam, OMC Reflected Beam, ETMx Transmission Monitor, ETMy transmission monitor, and AP2 Output Beam. There are two types of viewports: optical quality viewports and camera viewports.

1.2.1 Interferometer (IFO) Input Beam

The Interferometer Input Beam is comprised of the following assemblies:

1.2.1.1 Input Monitor

The Input Monitor consists of the following elements: beam pointing angle sensor, lateral beam displacement sensor, optical spectrum analyzer, and video camera intensity monitor.

1.2.1.2 IMC Mode Matching Optics

The Mode Matching Optics for the Input Mode Cleaner consists of a lens pair.

1.2.1.3 Input Beam Power Control

The Input Beam Power Control consists of a half-wave polarization rotator, a double-exit polarizing prism, a beam dump, and a power monitor.

1.2.1.4 IMC Beam Steering

The IMC Beam steering optics consists of a pair of piezoelectric-actuated steering mirrors and several turning mirrors.

1.2.1.5 Input Mode Cleaner (IMC)

The input mode cleaner is a triangular ring cavity comprised of three suspended mirrors with active damping.

1.2.1.6 Input Faraday Isolator

The input Faraday Isolator consists of an input Brewster's angle polarizing prism, a TGG crystal Faraday rotator, a half-wave polarization rotator, and an output Brewster's angle polarizing prism.

1.2.1.7 IFO Mode Matching Telescope

The IFO Mode Matching Telescope consists of an off-axis reflecting parabolic telescope with motorized focus adjustment.

1.2.1.8 IFO Beam Steering

The IFO Beam steering optics consists of a pair of piezoelectric-actuated steering mirrors located inside the vacuum chamber.

1.2.2 Optical Sensing Beams

1.2.2.1 Initial Pointing Beam

The Initial Pointing Beam is sampled with a beam splitter from the main IFO beam. Several turning mirrors direct the beam through the end chamber viewport onto a zoom position sensor.

1.2.2.2 IMC Reflected Beam

The IMC Reflected Beam sensing system is located on an external optical table. It consists of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter, photodetector, EO shutter, two wave-front sensing channels, a length sensing photodetector, and a video camera.

1.2.2.3 IMC Transmitted Beam

The IMC Transmitted beam sensing system is located on an external optical table. It consists of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter, RF photodetector, a photodetector, an optical spectrum analyzer, and a video camera.

1.2.2.4 Symmetric Port Signal

The Symmetric Port Signal (SPS) beam sensing system is located on an external optical table. It consists of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter, photodetector, EO shutter, a wave-front sensing channel, two length sensing photodetectors, a beam position detector, an optical spectrum analyzer, and a video camera.

1.2.2.5 ITM_x, ITM_y, and BS Pickoff Beams

The PO beam sensing systems is located on external optical tables. They consist of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter two wave-front sensing channels, two length sensing photodetectors, an optical spectrum analyzer, and a video camera.

1.2.2.6 AP1 Output beam

The AP1 Output beam sensing system is located on an external optical table. It consists of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter, photodetector, EO shutter, two wave-front sensing channels, two length sensing photodetector arrays, a beam position detector, an optical spectrum analyzer, and a video camera.

1.2.2.7 OMC Reflected Beam

The OMC Reflected Beam sensing system is located on an external optical table. It consists of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter, photodetector, EO shutter, two wave-front sensing channels, a length sensing photodetector, and a video camera.

1.2.2.8 ETM_x and ETM_y Transmission Monitor

The ETM Transmission monitors provide signals for controlling the pointing the main beam into the IFO arm.

1.2.2.9 AP2 Output Beam

The AP2 Output beam sensing system is located on an external optical table. It consists of the following elements: various turning mirrors, beam splitters, lenses, mechanical beam shutter, photodetector, EO shutter, two wave-front sensing channels, a length sensing photodetector, and a video camera.

1.2.3 Viewport

1.2.3.1 Optical Quality Viewport

1.2.3.2 Camera Viewport

1.3 Definitions

TBD

Define all terms used in the document as necessary to interpret its contents. For example, a CDS specification may make use of terminology, such as “real-time software”, which is subject to interpretation. This section should specifically define what “real-time software” means in the context of this document.

NOTE: This should include all standard names used in interface discussions/drawings.

1.4 Acronyms

AOM – Acousto-optic modulator

AP1 - antisymmetric port signal, transmitted through the Signal Recycling mirror

AP2 - antisymmetric port signal, transmitted through the output mode cleaner

AR - Antireflection Coating

ASC - Alignment Sensing and Control

BRDF - Bi-directional Reflectance Distribution Function

BS - Beam Splitter

BSC - Beam Splitter Chamber

CDS – Control and Data Systems

COC - Core Optics Components

COS - Core Optics Support

DRD - Design Requirements Document

EO - Electro-optic

EOM - Electro-optic modulator (Pockel's cell)

ETM_x, ETM_y - End Test Mass in the interferometer 'X' or 'Y' arm

GBAR - Ghost Beam from AR side of COC

GBHR - Ghost Beam from HR side of COC

HR - Reflective mirror coating

IAS- Initial Alignment System

IFO - interferometer

IMC - Input mode cleaner

IMC_R - Input mode cleaner reflected

IMC_T - Input mode cleaner transmitted

IOO - Input Optics

IPB- Initial Pointing Beam

ISC- Interferometer Sensing and Control

ITM_x, ITM_y - Input Test Mass in the interferometer 'X' or 'Y' arm

LIGO - Laser Interferometer Gravity Wave Observatory

LSC - Length Sensing and Control

MTBF - Mean time before failure

MTTR - Mean time to repair

OMC - Output Mode Cleaner

OMC_R - output mode cleaner reflected

OMC_T - Output mode cleaner transmitted

OptLev - Optical Lever

PO - Pick-off

ppm - parts per million

PRM - Power Recycling Mirror

1.5 Applicable Documents

1.5.1 LIGO Documents

Conceptual Design of the 40 Meter Laboratory Upgrade for Prototyping an Advanced LIGO Interferometer, LIGO T010029

Effect of PO Telescope Aberrations on Wavefront Sensor Performance, LIGO-T980007-00-D

LIGO Vacuum Compatibility, Cleaning Methods and Procedures, LIGO-E960022-00-D

LIGO-E000007-00

LIGO Naming Convention (LIGO-E950111-A-E)

LIGO Project System Safety Management Plan LIGO-M950046-F

LIGO EMI Control Plan and Procedures (LIGO-E960036)

Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D)

LIGO-E000408, ITM

E000410, specification ETM

E000413, specification BS

E000409, specification RM

D970535, specification MC flat

D970534, specification MC curved

1.5.2 Non-LIGO Documents

2 General description

2.1 Product Perspective

The relationships between the various subsystems and the entire IFO optical system can be seen in the following layout drawings.

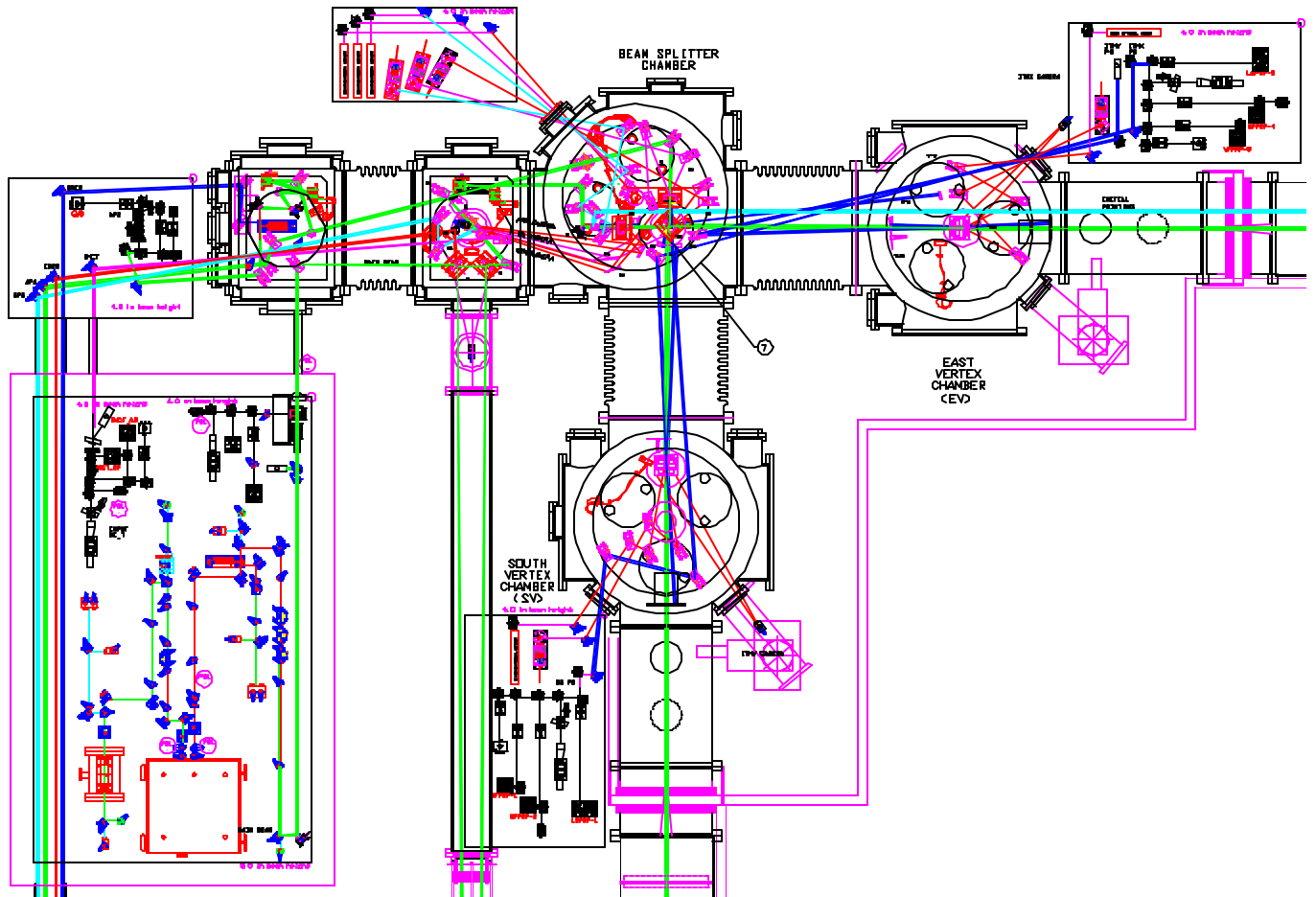


Figure 1: 40 m IFO vertex section

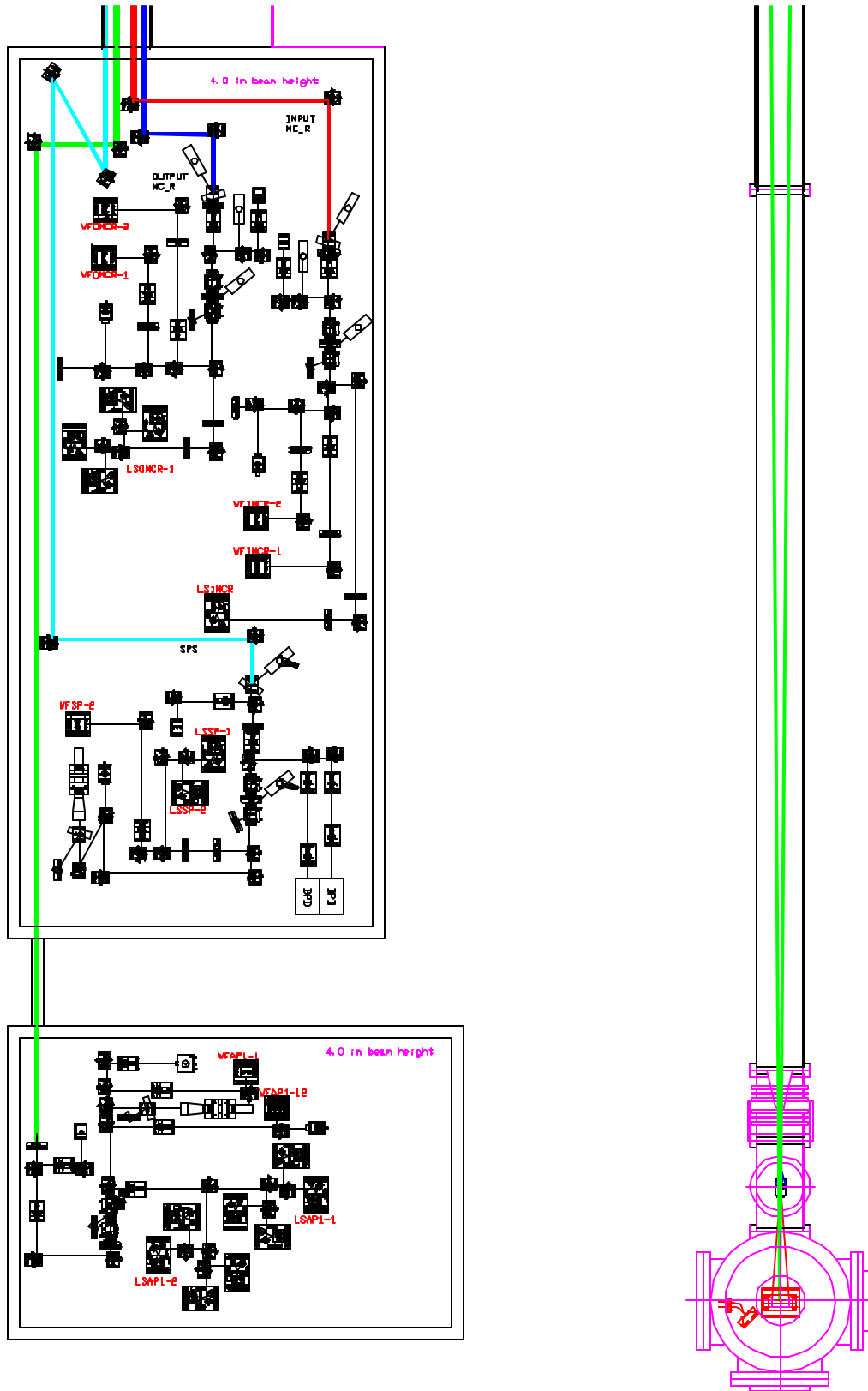


Figure 2: 40 m IFO mode cleaner section

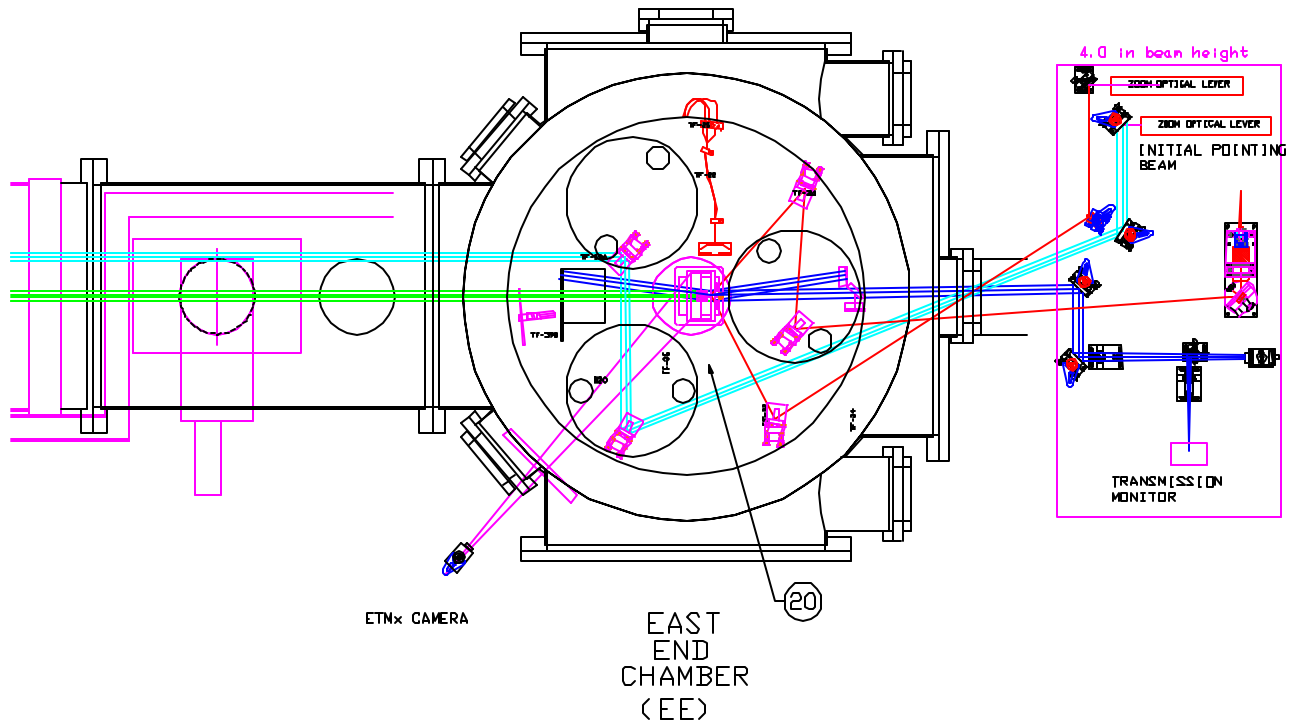


Figure 3: 40 m IFO end section

2.1.1 Interferometer (IFO) Input Beam

The Interferometer Input Beam receives the PSL beam and transforms it into a beam with stable spatial characteristics that are matched efficiently to the Interferometer mode.

2.1.1.1 Input Monitor

The Input Monitor provides measurements of the following beam properties: beam pointing angle, lateral beam displacement, optical frequency, and visual spatial beam intensity.

2.1.1.2 IMC Mode Matching Optics

The Mode Matching Optics for the Input Mode Cleaner consists of a lens pair that transforms the beam waist of the PSL beam into a new beam waist of the optimum size and location at the Input Mode Cleaner.

2.1.1.3 Input Beam Power Control

The Input Beam Power Control consists of a polarization rotator and a polarizing prism for varying the input laser power to the IFO, a beam dump for collecting the reflected power, and a power monitor.

2.1.1.4 IMC Beam Steering

A pair of piezoelectric-actuated steering mirrors provides angular and lateral position alignment of the input beam into the IMC.

2.1.1.5 Input Mode Cleaner (IMC)

The input mode cleaner is a spatial and temporal filter for the main IFO input beam. It is a triangular ring cavity comprised of three suspended mirrors. The IMC provides high transmissivity for the TEM₀₀ beam and low transmissivity for higher order beams. The free spectral range of the IMC allows passage of the IFO carrier frequency and the three side-band frequencies that are used for interferometer sensing and control (ISC).

2.1.1.6 Input Faraday Isolator

The input Faraday Isolator blocks the light power reflected from the IFO symmetric port and reflects the SPS output beam.

2.1.1.7 IFO Mode Matching Telescope

The IFO Mode Matching Telescope consists of an off-axis reflecting parabolic telescope that transforms the beam waist of the IMC beam into a new beam waist of the optimum size and location at the IFO

2.1.1.8 IFO Beam Steering

A pair of piezoelectric-actuated steering mirrors provides angular and lateral displacement alignment of the input beam into the input mode cleaner.

2.1.2 Optical Sensing Beams

The Interferometer Sensing and Control (ISC) beams provide signals for controlling the longitudinal position and angular orientations of the main IFO mirrors, for controlling the pointing of the beams into the input mode cleaner, the output mode cleaner, and the main interferometer, for controlling the frequency of the laser, and for detecting gravity waves.

2.1.2.1 Initial Pointing Beam

This beam is used to monitor the angular direction of the main input beam into the IFO. The initial pointing beam will be created by sampling a portion of the main IFO beam with a beamsplitter after the final steering of the main beam toward the RM. The initial pointing beam will be directed through the viewport in the East end chamber, onto the external optical table, and into the zoom optical receiver by means of steering mirrors located on the end chamber optical table and on the external optical table.

2.1.2.2 IMC Reflected Beam

The beam reflected from the input mode cleaner is used to provide signals for controlling the angular and lateral position orientation of the input beam to the IMC.

2.1.2.3 IMC Transmitted Beam

The beam transmitted through the IMC is used to control the frequency of the PSL beam.

2.1.2.4 Symmetric Port Signal

The Symmetric Port Signal (SPS) beam is used to provide signals for controlling the longitudinal position and angular orientations of the main IFO mirrors.

2.1.2.5 ITM_x, ITM_y, and BS Pickoff Beams

The ITM_x PO beam provides signals for controlling the longitudinal position and angular orientations of the main IFO mirrors. The ITM_x, ITM_y, and BS beams are redundant, and only one of the three is used at any one time. The ITM_x and ITM_y PO beams will exit the vacuum system through a common viewport window.

2.1.2.6 AP1 Output beam

The AP1 Output beam provides signals for controlling the longitudinal position and angular orientations of the main IFO mirrors.

2.1.2.7 OMC Reflected Beam

The beam reflected from the output mode cleaner is used to provide signals for controlling the longitudinal position and angular orientations of the input beam to the OMC.

2.1.2.8 ETM_x and ETM_y Transmission Monitor

The ETM Transmission monitors provide signals for controlling the pointing of the main beam into the IFO arms.

2.1.2.9 AP2 Output Beam

The AP2 Output beam provides the signal that is used for gravity wave detection.

2.1.3 Viewport

2.1.3.1 Optical Quality Viewport

Provides optical window for main IFO beam, output sensing beams, and optical lever beams.

2.1.3.2 Camera Viewport

Provides optical window for viewing the COC mirrors with visible and IR video cameras.

2.2 Product Functions

2.2.1 Interferometer (IFO) Input Beam

The functions of the Interferometer Input Beam are described in the following:

2.2.1.1 Input Monitor

- measures IMC input beam angular orientation
- measures IMC input beam displacement
- measures IMC input beam optical spectrum
- video image of IMC input beam cross-section
- monitors the input laser power to the IFO

2.2.1.2 IMC Mode Matching Optics

- transforms the beam waist of the PSL beam into a new beam waist of the optimum size and location

2.2.1.3 Input Beam Power Control

- controls the input laser power to the IFO

2.2.1.4 IMC Beam Steering

- provides the angular and lateral alignment of the input beam into the input mode cleaner at a specified band width.

2.2.1.5 Input Mode Cleaner (IMC)

- transmits the TEM00 spatial mode
- reflects higher order spatial modes
- transmits beams with carrier frequency
- transmits beams with the three side-band frequencies used for interferometer sensing and control

2.2.1.6 Input Faraday Isolator

- blocks the reflected beam from the IFO symmetric port
- extracts the SPS beam.

2.2.1.7 IFO Mode Matching Telescope

- transforms the beam waist of the IMC beam into a new beam waist of the optimum size and location at the IFO

2.2.1.8 IFO Beam Steering

- provide angular and lateral alignment of the input beam into the IFO at a specified bandwidth.

2.2.2 Optical Sensing Beams

2.2.2.1 Initial Pointing Beam

- monitors the angular alignment of the main input beam into the IFO

2.2.2.2 IMC Reflected Beam

- provide angle and position wave-front signals for the input beam to the IMC
- provides RF frequency measurement of IMC input beam
- provides a light-actuated EO shutter to protect the ISC optical sensors
- video image of reflected IMC beam cross-section

2.2.2.3 IMC Transmitted Beam

The beam transmitted through the IMC is used to control the frequency of the PSL beam and to measure the amplitude of the RF side bands.

2.2.2.4 Symmetric Port Signal

- provides angle and position wave-front signals for COC mirror control
- provides length sensing signal for COC mirror control
- provides bulls eye photodetector for input beam alignment diagnostics
- provides a light-actuated EO shutter to protect the ISC optical sensors
- provides video image of SPS beam cross-section
- measures optical spectrum of IFO reflected beam

2.2.2.5 ITM_x, ITM_y, and B S Pickoff Beams

- provides angle and position wave-front signals for COC mirrors
- provides length sensing signal
- provides video image of PO beam cross-section
- measures optical spectrum of Michelson cavity beam

Note: the ITM_x, ITM_y, and BS beams are redundant, and only one of the three is used at any one time.

2.2.2.6 AP1 Output beam

- provides angle and position wave-front signals for COC mirrors
- provides length sensing signal
- provides a light-actuated EO shutter to protect the ISC optical sensors
- provides video image of AP1 beam cross-section
- measures optical spectrum of IFO transmitted beam

2.2.2.6.1 Output Faraday Isolator

- isolates the IFO from reflected and scattered light from the AP1 and AP2 optical trains

2.2.2.6.2 AP1 Focus Lens

- reduces the beam size at the AP1 ISC table

2.2.2.6.3 AP1 Optical Train Assembly

- directs the AP1 beam to the external ISC table

2.2.2.7 OMC Reflected Beam

- provides angle and position wave-front signals for the input beam to the OMC
- provides a light-actuated EO shutter to protect the ISC optical sensors
- provides video image of reflected OMC beam cross-section

2.2.2.8 ETM_x and ETM_y Transmission Monitors

- monitors the lateral beam position and power at the ETM mirrors

2.2.2.9 AP2 Output Beam

- The AP2 Output beam provides the signal that is used for gravity wave detection.

2.2.2.9.1 Mode Matching Telescope, OMC

- matches the beam waist and position to the OMC cavity

2.2.2.9.2 Beam Steering, OMC

- provides angular and lateral position of the input beam into the output mode cleaner at a specified deflection bandwidth.

2.2.2.9.3 Output Mode Cleaner

- Eliminates higher order modes from the output beam
- Eliminates all side-band frequencies except for the gravity wave band.

2.2.2.9.4 AP2 Optical Train Assembly

2.2.3 Viewport

2.2.3.1 Optical Quality Viewport

- Provides an optical window on the vacuum chamber with low wavefront distortion and high transmissivity for the main IFO beam, the ISC beams, and some optical lever beams.

2.2.3.2 Camera Viewport

- Provides an optical window on the vacuum chamber for transmitting optical lever beams and for viewing inside the chamber with an IR video camera.

2.3 General Constraints

The Optical Systems and Sensing design is constrained by the requirements of the Conceptual Design of the 40 Meter Laboratory Upgrade for Prototyping an Advanced LIGO Interferometer, LIGO T010029.

The assumptions and dependencies that affect the design are listed in the following section.

2.3.1 Core Optics Parameters

See Core Optics Specifications: LIGO-E000408, ITM; E000410, ETM; E000413, BS; E000409, RM; D970535, MC flat; D970534, MC curved

Table 1: Core Optics Parameters

Physical Quantity	PRM	SRM	BS	ITM	ETM
AR coating @ 1060 nm	<0.0005	<0.0005	0.0006	0.0006	<0.0005
AR coating @ 940 nm	>0.4	>0.4	>0.4	>0.4	NA
Substrate thickness, mm	28	28	28	50	50
Mirror power loss fraction	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
Mirror reflectivity @ 1060 nm	0.93	0.93	0.5	0.995	0.9999625
Mirror reflectivity @ 940 nm	>0.4	>0.4	>0.4	>0.4	>0.4
Mirror reflectivity @ 670 nm	>0.04	>0.04	>0.04	>0.04	>0.04
Refractive index @ 1064 nm	1.44963	1.44963	1.44963	1.44963	1.44963
Beam waist, mm	3.04	3.04	3.03	3.03	5.24
1ppm power contour radius, mm	7.97	7.98	7.97	7.96	13.8
Mirror diameter, mm	75	75	75	125	125

Mirror thickness, mm	25	25	25	50	50
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2.3.2 Interferometer Design Parameters

The stray light calculations were based on the following assumed parameters:

Table 2: Interferometer Design Parameters

Laser input power	6 W
SPS power	0.06 W
AP1 power	0.03 W
AP2 power	0.03 W
IFO Gaussian beam radius, w	3.03 mm
Recycling cavity gain	14
Arm cavity gain	767

3 Requirements

3.1 Interferometer (IFO) Input Beam

The interferometer input beam consists of the following elements: mode matching optics for the input mode cleaner (IMC), servo-controlled beam steering into the IMC, the IMC, the Input Faraday Isolator, the mode matching telescope into the IFO, and servo-controlled beam steering into the IFO.

3.1.1 Input Monitor

3.1.1.1 Introduction

The purpose of the input beam monitor is to measure the following properties of the input laser beam to the IFO: beam position and beam pointing angle after the input mode cleaner steering mirrors, power level, laser frequency spectrum, beam intensity profile.

A layout drawing of the input monitor is shown in Figure 4: Input Monitor Layout. The input beam to the IMC, after the steering mirror at the top of the input periscope, is sampled with a 1% reflectivity beam splitter cube mounted at the top of the periscope, as shown in Figure 5: Input monitor pick-off. A position sensing quad photodetector is located at an image of the angle steering and monitors the position of the beam on the angle steering mirror. The deflection angle of the beam is multiplied by a beam-reducing telescope, and an angle sensing quad photodetector placed at the focal plane of a lens converts angle to beam displacement and monitors the angular pointing of the beam into the IMC. The sum of the quad photodetector signals is used to measure the total power sampled. A spectrum analyzer measures the frequency spectrum. The sample beam is focused onto a video camera to display the intensity profile of the beam.

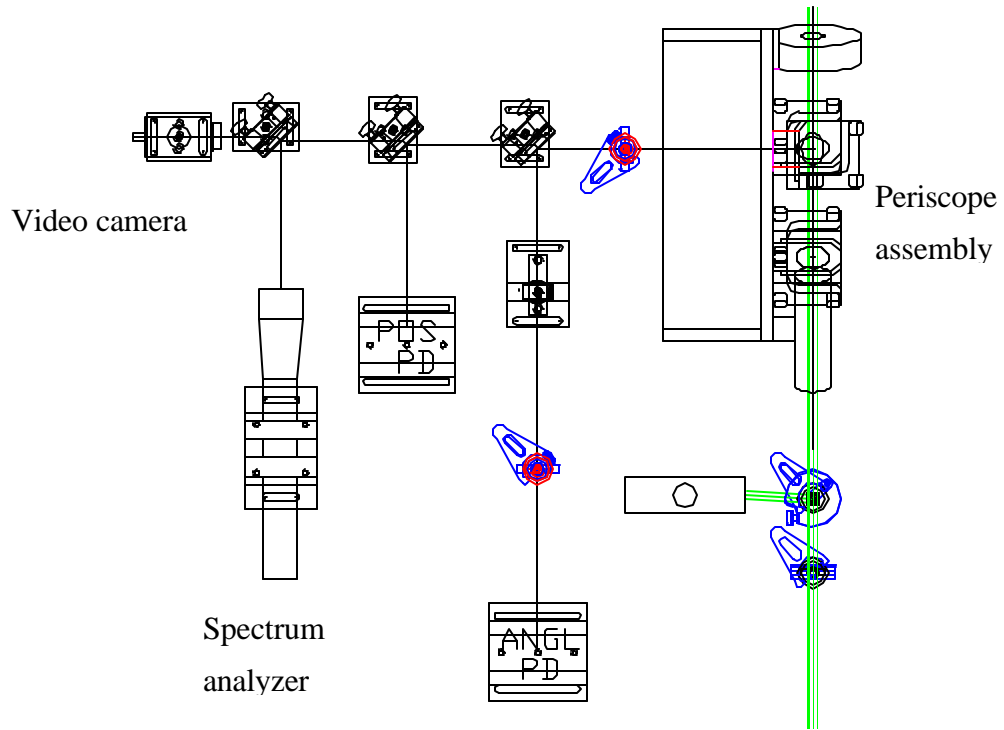


Figure 4: Input Monitor Layout

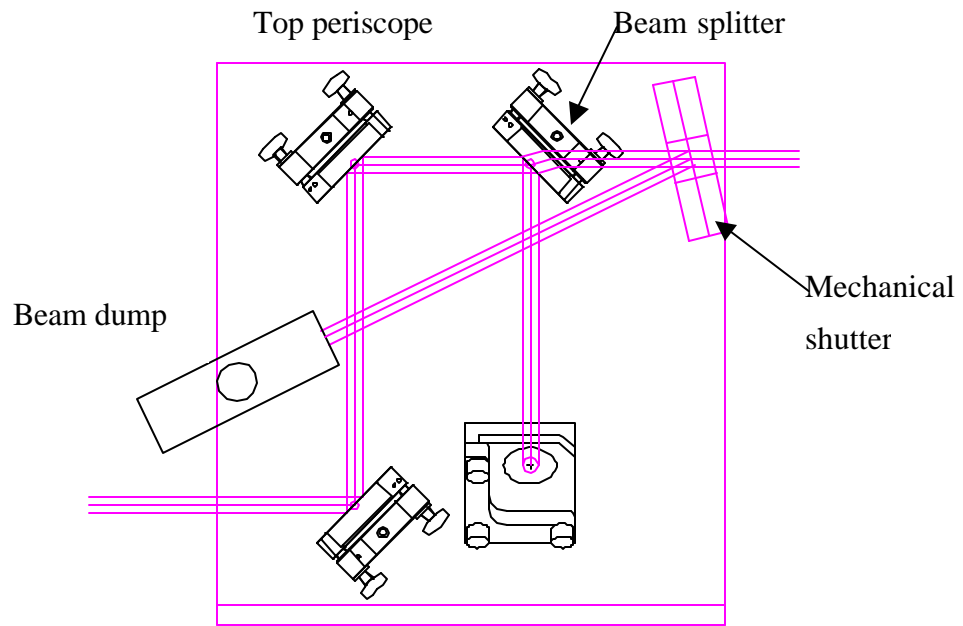


Figure 5: Input monitor pick-off, elevation view

3.1.1.2 Input Monitor Characteristics

3.1.1.2.1 Input Monitor Performance Characteristics

The input monitor shall measure the properties of the input laser beam into the IMC to an accuracy that is sufficient to enable reproducing the input laser conditions into the IMC, without causing a significant disturbance to the input beam.

The sampled power fraction shall be < 1% of the incident beam power. The beam position measurement accuracy shall be < 10% of the beam diameter at the input mode cleaner. The beam angular pointing measurement resolution shall be < 10% of the divergence angle of the beam at the input mode cleaner.

3.1.1.2.1.1 Displacement Sensor

The beam position at of the quad position sensor as a function of beam position at the angle steering mirror is linear, as shown in Figure 6: Position sensor response. The cross coupling between input beam angle and position signal at the quad position sensor is negligible, as shown by the three superimposed position response curves in which the beam angle varies from 0 – 0.02 rad.

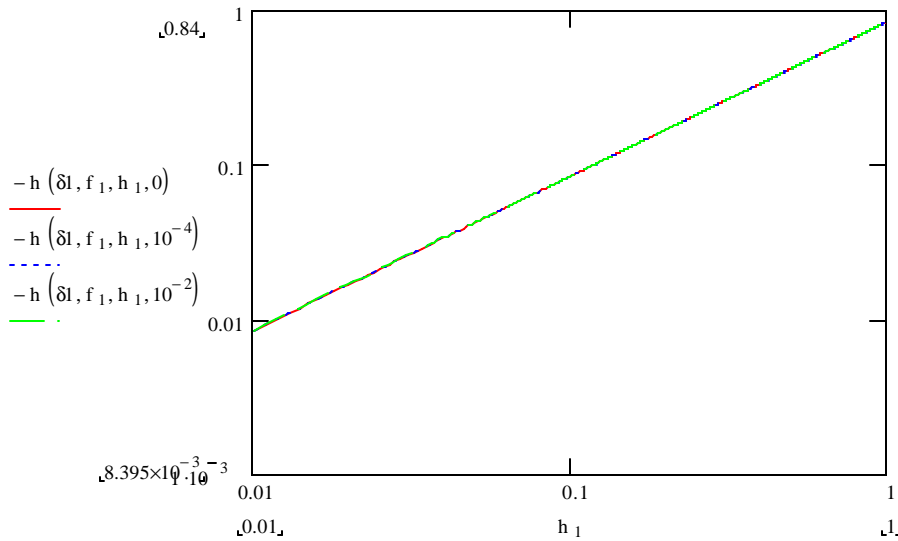


Figure 6: Position sensor response

Table 3: Summary of displacement sensor performance characteristics

Parameter	Requirement	Actual
position ratio, mm/mm		-0.84
Cross coupling, mm/rad		-1.07E-13
Beam displacement resolution, mm	< 0.16	0.02
Beam sample fraction	< 1%	1% sample

3.1.1.2.1.2 Angle Sensor

The beam position at the quad angle sensor as a function of beam angle at the angle steering mirror is linear, as shown in Figure 7: Angle sensor response. The cross coupling between input beam position and angle signal is negligible, as shown by the three superimposed angle response curves in which the beam position varies from 0 – 2 mm.

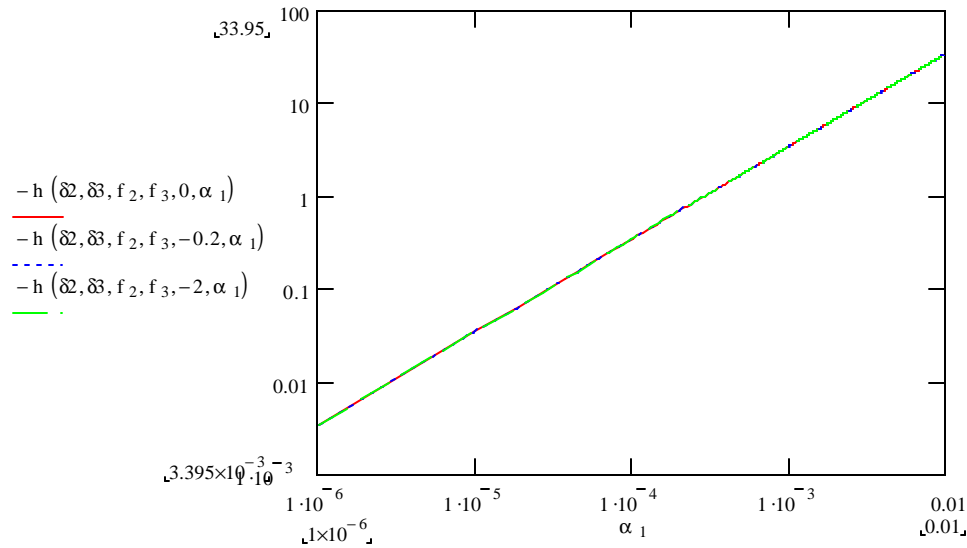


Figure 7: Angle sensor response

Table 4: Summary of angle sensor performance characteristics

Parameter	Requirement	Actual
Transfer ratio, mm/rad		-3400
Cross coupling, rad/mm		0
Beam angular pointing resolution, rad	2E-5	3E-6
Beam sample fraction	< 1%	1% sample

3.1.1.2.1.3 Power detector

Table 5: Summary of power detector performance characteristics

Parameter	Requirement	Actual
TBD		

3.1.1.2.1.4 Spectrum Analyzer

Table 6: Summary of spectrum analyzer performance characteristics

Parameter	Requirement	Actual
TBD		

3.1.1.2.1.5 Video Camera

Table 7: Summary of video camera performance characteristics

Parameter	Requirement	Actual
Wavelength range	500-1064 nm	500-1064 nm
Sensitivity		TBD
Resolution		TBD

3.1.1.2.2 Input Monitor Physical Characteristics

Table 8: Summary of Input Monitor physical characteristics

Parameter	Requirement	Actual
Wavelength range	1064 nm	1064 nm
Displacement sensor		Quad photodiode
Angle sensor		Quad photodiode
Video camera		Watec
Optical spectrum analyzer		Coherent

3.1.1.2.3 Input Monitor Interface Definitions

3.1.1.2.3.1 Interfaces to other LIGO detector subsystems

3.1.1.2.3.1.1 Mechanical Interfaces

The input monitor beam splitter and steering mirror will mount to the IO periscope. The input monitor optical train will mount to the PSL table with a beam height of 4.00 in.

3.1.1.2.3.1.2 Electrical Interfaces

The displacement QPD, angle QPD, optical spectrum analyzer, and video camera will have interfaces to CDS.

3.1.1.2.3.1.3 Optical Interfaces

The input monitor beam splitter will be centered on the IO input beam to the IMC

3.1.1.2.4 Input Monitor Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.1.1.3 Input Monitor Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.1.1.4 Input Monitor Qualification

Test and acceptance criteria. TBD

3.1.2 IMC Mode Matching Optics

3.1.2.1 Introduction

The IMC mode matching optics shall transform the Gaussian beam waist of the PSL beam located at the second RF Pockel's cell into a new beam waist of the optimum size at the location midway between the IMC1 and IMC3 mirrors.

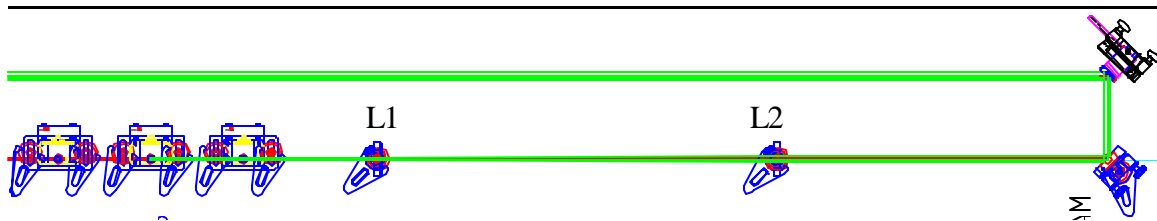


Figure 8: Input mode cleaner mode-matching lenses

3.1.2.2 IMC Mode Matching Optics Characteristics

3.1.2.2.1 IMC Mode Matching Optics Performance Characteristics

The wavefront distortion of the lenses shall not reduce the available laser power into the IFO by a significant amount (<5% power loss). The surface quality, reflection losses, and internal losses of the lenses shall not be excessive at 1064nm wavelength. The power coupling error into the input mode cleaner shall not reduce the available laser power into the IFO by a significant amount (<5% power loss).

Table 9: IMC Mode Matching Optics, Characteristics

Parameter	Requirement	Actual
L1 focal length @ 1064 nm, mm		-229.1
Clear aperture L1, mm	2.51	22
L2 focal length @ 1064 nm, mm		687.5
Clear aperture L2, mm	10.4	22
Input beam waist radius, mm	0.367	.367
Distance to first lens, mm		340
Distance to second lens, mm		547.5
Output beam waist radius, mm	1.63 +/- 0.36	1.64
Raleigh range of mode cleaner waist, mm		7835
Output beam location error, mm	3500	42
Power coupling error	5%	<0.1%
Substrate material		UV grade fused silica
Surface figure		$\lambda/10$ @ 633nm
Surface quality, scratch and dig		10-5 laser quality
Antireflection coating, per surface		<0.3 @ 1064 nm

3.1.2.2.1.1 Power Coupling into IMC

The power coupled into the input mode cleaner depends upon how well the waist size and waist location are matched to the input mode cleaner values. The power coupling loss due to the waist size mismatch and waste location mismatch is calculated by the following equations:

$$f_w(l_1, l_2, f_1, f_2) := \left[\frac{(w_{mc0}(l_1, l_2, f_1, f_2) - w_{imcref})}{w_{imcref}} \right]^2$$

$$f_z(l_1, l_2, f_1, f_2) := \left[\frac{(l_{40}(l_1, l_2, f_1, f_2) - l_4(l_1, l_2))}{2 \cdot z_R} \right]^2$$

The total power coupling loss is the sum of the two losses and is plotted in Figure 9: Total power coupling error into IMC, as a function of the distance between the two mode matching lenses. The first lens is placed a fixed distance 340 mm away from the input beam waist at the center of the RF Pockel’s cell. The effect of a 1% variation in focal length of the secondary mirror nominal value of 687.5 mm is shown by the parametric curves in Figure 9: Total power coupling error into IMC.

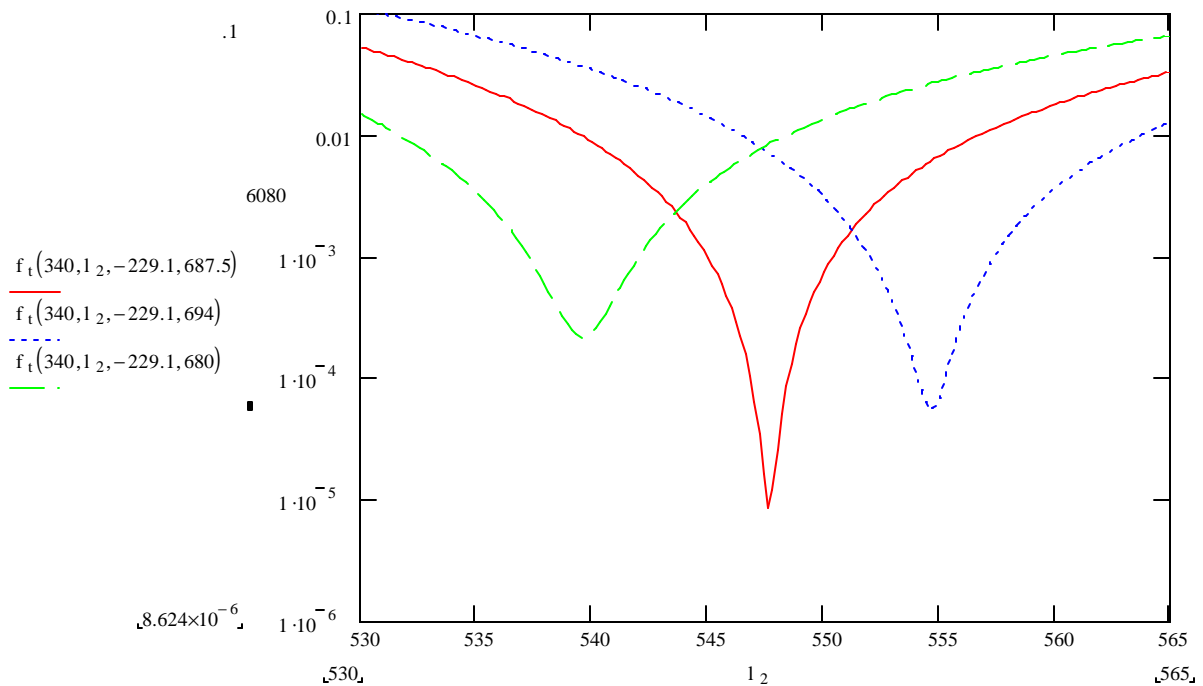


Figure 9: Total power coupling error into IMC

3.1.2.2.2 IMC Mode Matching Optics Physical Characteristics

The mode matching optics shall be compatible with standard 1inch optical mounts.

3.1.2.2.3 IMC Mode Matching Optics Interface Definitions

3.1.2.2.3.1 Interfaces to the PSL optical beam

3.1.2.2.3.1.1 Mechanical Interfaces

The IMC mode matching lens holders will be mounted on the same optical table with the PSL subsystem, and the RF modulation subsystem and shall not interfere with these subsystems.

3.1.2.2.3.1.2 Optical Interfaces

The IMC mode matching lenses will be placed on the optical centerline of the PSL output beam.

3.1.2.2.4 IMC Mode Matching Optics Reliability

These are passive elements, and after installation the MTBF is estimated to be the life of the IFO.

3.1.2.3 IMC Mode Matching Optics Precedence

3.1.2.4 IMC Mode Matching Optics Qualification

The lenses and mounts shall be inspected visually for compliance with the device specifications

3.1.3 Input Beam Power Control

3.1.3.1 Introduction

The input beam power control shall provide a means for varying the input laser power to the IFO. It consists of a manually rotatable half-wave plate and a polarization beam splitter, as shown in Figure 10: Input beam power control system.

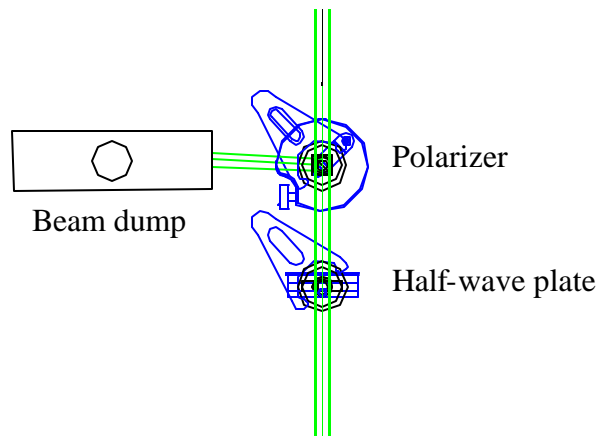


Figure 10: Input beam power control system

3.1.3.2 Input Beam Power Control Characteristics

3.1.3.2.1 Input Beam Power Control Performance Characteristics

The input beam power control system shall vary the transmitted power by a factor of 100. The insertion loss of the power control system shall be $< 2\%$.

Table 10: Summary of Input Beam Power Control performance characteristics

Parameter	Requirement	Actual
Wavelength	1064 nm	1064 nm
Polarizing beam splitter		
Extinction ratio	> 100:1	> 1000:1
Transmissivity	> 97%	> 98%
Half-wave plate		
Type		Zero order
Retardation tolerance		< 1% ellipticity
Transmissivity		> 99.7%

3.1.3.2.2 Input Beam Power Control Physical Characteristics

Table 11: Summary of Input Beam Power Control physical characteristics

Parameter	Requirement	Actual
Polarizing beam splitter		
Material		Calcite, Brewster's angle
Wavefront distortion		< ¼ wave @ 633nm
Half-wave plate		
Surface quality		10-5 laser quality
Material		Crystalline quartz
Wavefront distortion		< ¼ wave @ 633nm

3.1.3.2.3 Input Beam Power Control Interface Definitions

3.1.3.2.3.1 Interfaces to other LIGO detector subsystems

3.1.3.2.3.1.1 Mechanical Interfaces

The input beam power control system is mounted on the PSL table.

3.1.3.2.3.1.2 Electrical Interfaces

The input beam power meter has an electrical interface to CDS.

3.1.3.2.3.1.3 Optical Interfaces

The input beam power half-wave plate and polarization beam splitter are centered on the main IFO input optical beam.

3.1.3.2.4 Input Beam Power Control Reliability

The input beam power control is comprised of passive optical components, and Mean Time Between Failures (MTBF) is expected to be the life of the IFO.

3.1.3.3 Input Beam Power Control Qualification

Test and acceptance criteria. TBD

3.1.4 IMC Beam Steering

3.1.4.1 Introduction

The IMC Beam Steering shall provide angular and lateral alignment of the input beam into the input mode cleaner at a specified deflection bandwidth.

The IMC beam steering is accomplished by two PZT tilt platforms steering mirrors. The displacement of the IMC beam is done by the PZT steering mirror located at the end of the PSL table, as shown in Figure 8: Input mode cleaner mode-matching lenses. The angle steering of the IMC beam is done by the second PZT steering mirror located at the top of the IO periscope, as shown in Figure 4: Input Monitor Layout.

3.1.4.2 IMC Beam Steering Characteristics

3.1.4.2.1 IMC Beam Steering Performance Characteristics

Table 12: Summary of IMC Beam Steering performance characteristics

Parameter	Requirement	Actual
Spot size @ IMC	1.6 mm	
Lateral displacement @ IMC	+/- 1.6 mm	+/- 2.9 mm
Divergence angle of IMC	0.21 mrad	
Angular tilt	+/- 0.21 mrad	+/- 1.0 mrad
Angular slew rate	TBD	TBD

3.1.4.2.2 IMC Beam Steering Physical Characteristics

Table 13: Summary of IMC Beam Steering physical characteristics

Parameter	Requirement	Actual
Steering mirror 1 size	14.7 mm	20 x 35 mm
Steering mirror 2 size	32 mm	20 x 35 mm

3.1.4.2.3 IMC Beam Steering Interface Definitions

3.1.4.2.3.1 Interfaces to other LIGO detector subsystems

3.1.4.2.3.1.1 Mechanical Interfaces

The IMC Beam Steering system is mounted on the PSL table.

3.1.4.2.3.1.2 Electrical Interfaces

The IMC Beam Steering PZT tilt platforms have electrical interfaces to CDS.

3.1.4.2.3.1.3 Optical Interfaces

The IMC Beam Steering mirrors are centered on the main IFO input optical beam.

3.1.4.2.3.1.4 Stay Clear Zones

3.1.4.2.4 IMC Beam Steering Reliability

Mean Time Between Failures (MTBF) of the IFO beam steering is the lifetime of the PZT tilt platform, which is expected to be the life of the IFO.

3.1.4.3 IMC Beam Steering Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.1.4.4 IMC Beam Steering Qualification

Test and acceptance criteria. TBD

3.1.5 Input Mode Cleaner (IMC)

3.1.5.1 Introduction

The input mode cleaner (IMC) shall transmit efficiently the TEM₀₀ spatial mode of the main input laser beam from the PSL, and shall reflect higher order spatial modes. It shall transmit the carrier frequency and beams with the three side-band frequencies that are used for interferometer sensing and control.

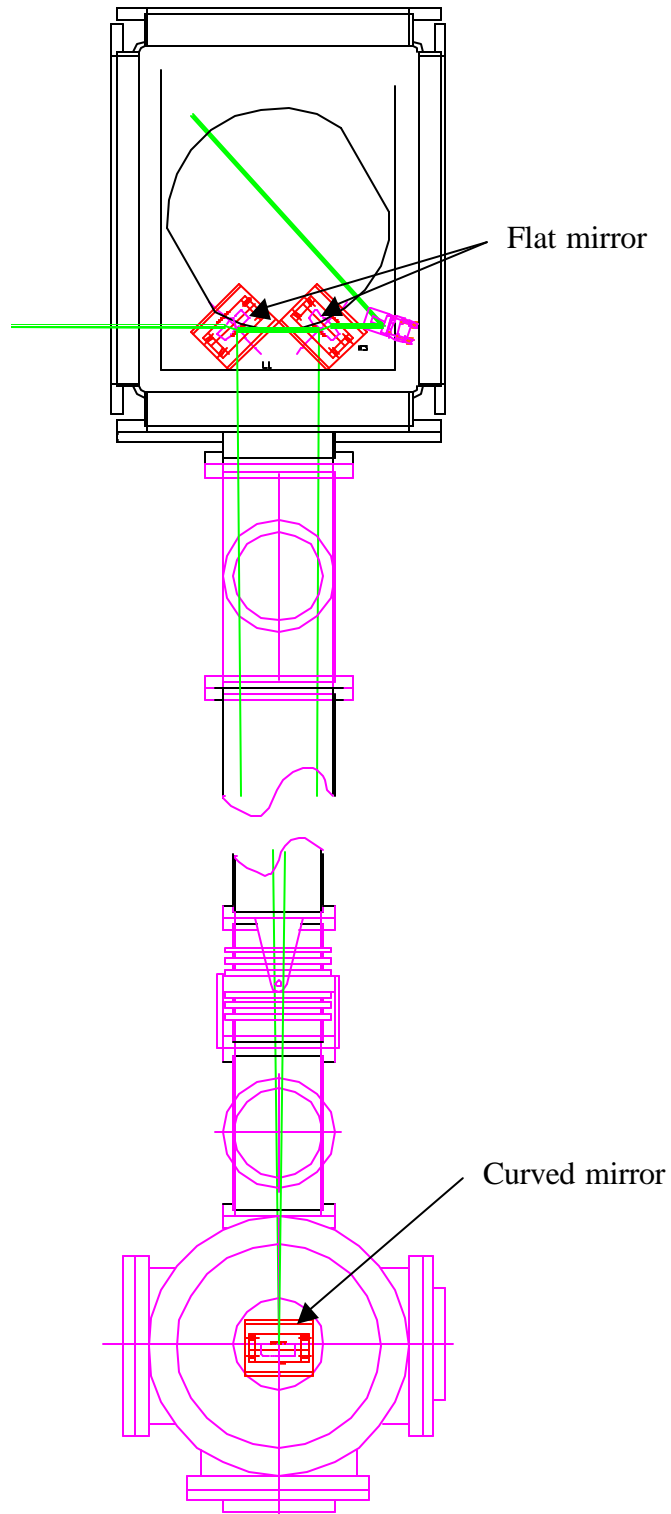


Figure 11: Input mode cleaner

3.1.5.2 Input Mode Cleaner Characteristics

3.1.5.2.1 Input Mode Cleaner Performance Characteristics

Table 14: Summary of IMC performance characteristics

Parameter	Requirement	Actual
Plane mirror transmittance	0.002	0.002
Plane mirror reflectance	0.998	0.998
Curved mirror transmittance	$< 1 \times 10^{-5}$	$< 1 \times 10^{-5}$
AR coating reflectivity	$< 0.2 \%$	$< 0.2 \%$
Mirror power loss	< 0.00010	< 0.00010
Finesse	1550	1550
Free spectral range	11.83 MHz	11.83 MHz
Power build-up factor	450	450
Transmissivity of IMC	$> 85 \%$	$> 85 \%$
Cavity bandwidth width/half max	7.56 kHz	7.56 kHz
Cavity optical half-length	12680 mm	12680 mm
$G = 1-L/R$	0.29	0.29
Waist size	1.657	1.657
1ppm diameter, curved mirror	16.17	16.17
Length control, dynamic range	27 micron pk-pk	27 micron pk-pk
Angle control, dynamic range	1.5 mrad pk-pk	1.5 mrad pk-pk
Length noise density	3×10^{-18} m/rtHz	3×10^{-18} m/rtHz

3.1.5.2.2 Input Mode Cleaner Physical Characteristics

Table 15: Summary of IMC physical characteristics

Parameter	Requirement	Actual
Mirror thickness		25.0 mm
Mirror wedge		30 min arc
Mirror diameter		75.0 mm
Curved mirror radius of curvature		17869 mm
Flat mirror radius of curvature		> 80000 mm
Coating diameter, flat mirror		70 mm
Coating diameter, curved mirror		25 mm

3.1.5.2.3 Input Mode Cleaner Interface Definitions

3.1.5.2.3.1 Interfaces to other LIGO detector subsystems

3.1.5.2.3.1.1 Mechanical Interfaces

The two flat mirrors of the IMC are suspended from a SOS structure and are mounted on the optics table in the input chamber. The curved mirror is suspended from an SOS structure and is mounted on the optics table in the mode-matching chamber.

3.1.5.2.3.1.2 Electrical Interfaces

The three suspended IMC mirrors are controlled by OSEMs, which have electrical interfaces to CDS.

3.1.5.2.3.1.3 Optical Interfaces

The two flat mirrors of the IMC are centered on the main IFO beam.

3.1.5.2.3.1.4 Stay Clear Zones

3.1.5.2.4 Input Mode Cleaner Reliability

Mean Time Between Failures (MTBF), Availability, TBD

3.1.5.2.5 Input Mode Cleaner Maintainability

Mean Time To Repair (MTTR); Qualitative requirements for accessibility, modular construction, test points, etc. TBD

3.1.5.3 Input Mode Cleaner Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.1.5.4 Input Mode Cleaner Qualification

Test and acceptance criteria. TBD

3.1.6 Input Faraday Isolator

3.1.6.1 Introduction

The input Faraday isolator shall attenuate the reflected and scattered light from the SPS sensor elements. The input Faraday isolator shall extract the SPS beam from the main IFO beam. The input Faraday isolator shall efficiently transmit the main IFO input beam and attenuate the reflected IFO beam that returns to the PS�.

The isolator assembly consists of an input polarizing prism, a Faraday rotator, an output polarizing prism, and a half-wave plate to rotate the polarization parallel to the optical table

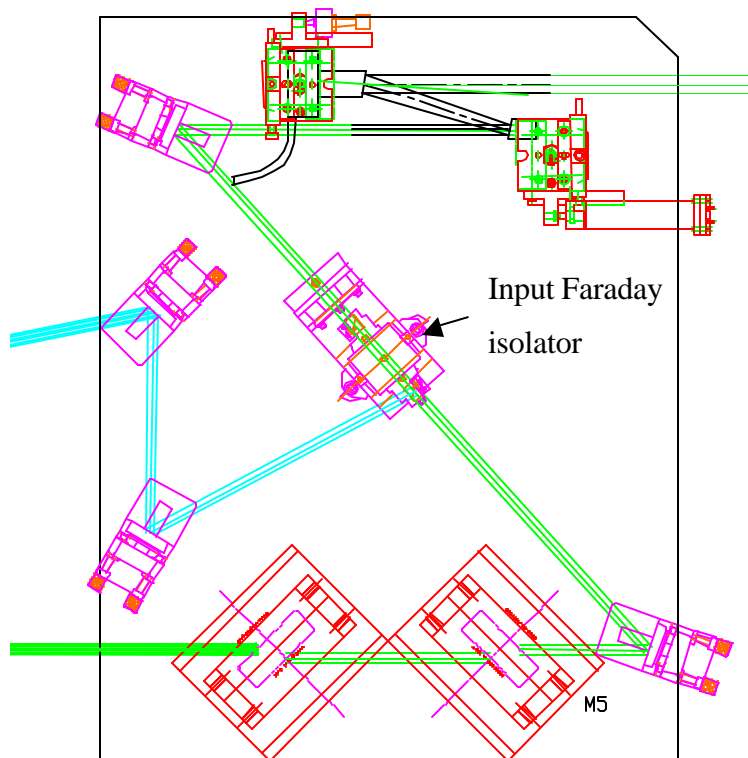


Figure 12: Input Faraday Isolator

3.1.6.2 Input Faraday Isolator Characteristics

3.1.6.2.1 Input Faraday Isolator Performance Characteristics

Table 16: Input Faraday Isolator Performance Characteristics

Parameter	Requirement	Actual
Wavelength	1064 nm	
Transmissivity across clear aperture		> 95%
Input polarization		Perpendicular to optical table
Output polarization		Parallel to optical table
Attenuation factor	1000:1	1000:1

3.1.6.2.2 Input Faraday Isolator Physical Characteristics

Table 17: Input Faraday Isolator Physical Characteristics

Parameter	Requirement	Actual
Clear aperture	8.7 mm	12.0 mm
Faraday material		TGG
Input polarizer		Brewster angle calcite
Input polarizer		Brewster angle calcite
Half-wave plate		Quartz, zero order

3.1.6.2.3 Input Faraday Isolator Interface Definitions

3.1.6.2.3.1 Interfaces to other LIGO detector subsystems

3.1.6.2.3.1.1 Mechanical Interfaces

The input Faraday isolator will mount to the optical table in the input chamber, aligned with the main beam at a beam height of 5.5 in.

3.1.6.2.3.1.2 Optical Interfaces

The input Faraday isolator will be centered with the axis of the main beam, and will be tilted slightly to avoid the glint of the SPS beam back into the interferometer.

3.1.6.2.4 Input Faraday Isolator Reliability

The Mean Time Between Failures (MTBF) of the Faraday Isolator is the life of the IFO.

3.1.6.2.5 Input Faraday Isolator Maintainability

Mean Time To Repair (MTTR) of the Faraday Isolator is the life of the IFO.

3.1.6.3 Input Faraday Isolator Precedence

3.1.6.4 Input Faraday Isolator Qualification

Test and acceptance criteria. TBD

3.1.7 IFO Mode Matching Telescope

The IFO mode-matching telescope shall transform the beam waist of the IMC beam into a new beam waist of the optimum size and location at the IFO with a minimum of power coupling loss and a minimum of scattering or glinting into the IFO.

3.1.7.1 Introduction

The main interferometer mode-matching telescope is an off-axis parabolic reflective telescope of the Mersenne type. Its function is to transform the input beam from the beam waist at the IMC to the IFO beam waist located at the ITM mirror surface. An all-reflective design was chosen to minimize the light scattering and glint into the IFO.

The spacing between the primary and secondary mirror can be varied remotely for focusing, while under vacuum, by means of the electric Pico motor. The secondary mirror is tilted with the fast response PZT tilt platform for dynamic beam steering.

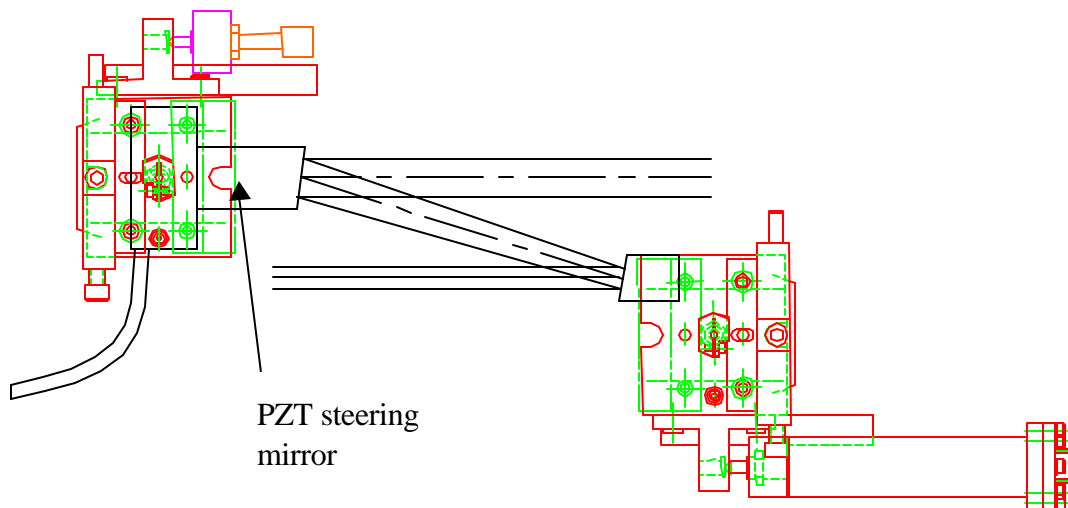


Figure 13: IFO mode matching telescope**3.1.7.2 IFO Mode Matching Telescope Characteristics****3.1.7.2.1 IFO Mode Matching Telescope Performance Characteristics****Table 18: IFO mode matching telescope performance characteristics**

Parameter	Requirement	Actual
Clear aperture M1, mm	8.8	19
Clear aperture M2, mm	16.1	25
Input beam waist radius, mm	1.66	1.66
Output beam waist radius, mm	3.027	3.029
Power coupling error	<0.05	< 0.001
Wavefront distortion		<0.2
Transmissivity across clear aperture		> 99.8%, ion beam dielectric coating
Magnification	1.8	1.8

3.1.7.2.2 IFO Mode Matching Telescope Physical Characteristics**Table 19: IFO mode matching telescope physical characteristics**

Parameter	Requirement	Actual
M1 focal length, mm		-168
M2 focal length @ 1064 nm, mm		687.5
Distance to M1, mm		1223
Distance to M2, mm		137.9
M1 off-axis distance, in		2.049
M2 off-axis distance, in		2.049
Substrate material		Zerodur

3.1.7.2.2.1 Optical Alignment

The telescope will be pre-aligned before assembly into the IFO vacuum housing.

3.1.7.2.2.2 Resonant Frequency of Elements Mounted on the Optics Platform

The resonant frequencies and Q's of the Telescope and accessory optics which are mounted to the optics platforms shall not induce excessive thermal-noise of the test mass.

3.1.7.2.3 IFO Mode Matching Telescope Interface Definitions

3.1.7.2.3.1 Interfaces to other LIGO detector subsystems

3.1.7.2.3.1.1 Mechanical Interfaces

The Telescope and associated optical train elements shall mount to the optical platform in the vacuum chambers, without interfering with the COC mirror structures.

3.1.7.2.3.1.2 Electrical Interfaces

Table 20: Electrical interfaces, IFO mode matching telescope

Parameter	Requirement	Actual
Secondary mirror tilt platform		
Power supply		-10, +150 V, 4 wires
Strain gage		8 wires
Pico motor focus		2 wires

3.1.7.2.3.1.3 Optical Interfaces

The Telescope shall provide a large enough field-of-view so that the IFO main beam will not vignette as a result of optical table motion after pump-down of the vacuum chambers.

3.1.7.2.3.1.4 Stay Clear Zones

All support components shall stay clear of the 1ppm diameter of the main IFO beam.

3.1.7.2.4 IFO Mode Matching Telescope Reliability

The telescope elements are passive and are expected to have a 100 % availability. The MTBF is expected to be equal to the life of the PZT tilt platform, or the life of the pico motor.

3.1.7.3 IFO Mode Matching Telescope Precedence

The relative importance of the telescope subsystem requirements is:

- 1) clear aperture through the telescope optical train
- 2) optical transmissivity through the telescope optical train

3) compatibility with COC elements

3.1.8 IFO Beam Steering

3.1.8.1 Introduction

The beam displacement and pointing angle of the IFO main beam will be steered remotely. The position of the IFO beam at the input to the power-recycling mirror (PRM) will be steered by means of a PZT tilt mirror mounted at the secondary mirror of the IFO mode matching telescope. The angle of the beam at the input to the recycling cavity will be steered by means of a PZT tilt mirror located near the PRM, as shown in Figure 14: IFO beam steering.

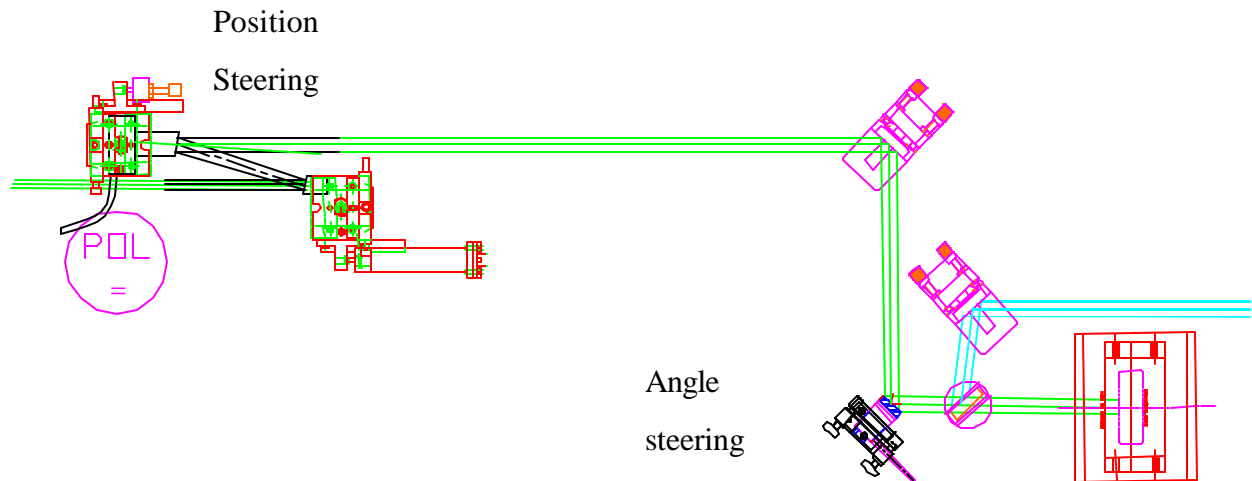


Figure 14: IFO beam steering

3.1.8.2 IFO Beam Steering Characteristics

3.1.8.2.1 IFO Beam Steering Performance Characteristics

Table 21: IFO beam steering performance characteristics

Parameter	Requirement	Actual
Spot size of IFO beam	3.03 mm	
Displacement steering	+/- 3.03 mm	+/- 4 mm
Divergence angle of IFO beam	0.00011 rad	
Angular steering	0.00011 rad	+/- 0.004 rad
Resonant frequency		3500 Hz
Angle sensing		Internal strain gage

3.1.8.2.2 IFO Beam Steering Physical Characteristics

Table 22: IFO beam steering physical characteristics

Parameter	Requirement	Actual
Stiffness		0.0005 N/micrometer
Voltage cable		LEMOSA, 4 wire
Sensor cable		LEMOSA, 8 wire
Weight		60 g
Dimensions:		
Diameter		25 mm
Length		29.5 mm

3.1.8.2.2.1 Vacuum compatibility of elements

3.1.8.2.2.1.1 Outgassing of elements

PZT-actuated steering mirrors and motor-actuated shutter devices will be fabricated from materials and processes that minimize the outgassing of the device.

3.1.8.2.3 IFO Beam Steering Interface Definitions

3.1.8.2.3.1 Interfaces to other LIGO detector subsystems

3.1.8.2.3.1.1 Mechanical Interfaces

The position-steering mirror will be mounted to the secondary mirror mount of the IFO mode-matching telescope on the optics table inside the input chamber. The angle-steering mirror will be mounted on the optics table inside the BS chamber.

3.1.8.2.3.1.2 Electrical Interfaces

X and y tilt drive voltages and strain gage sensor signals for the PZT tilt mirrors will be supplied through a vacuum feedthrough connector external to the vacuum chamber.

3.1.8.2.3.1.3 Optical Interfaces

The steering mirrors will be placed on the centerline of the main IFO beam and will not vignette the beam closer than the 1ppm beam diameter.

3.1.8.2.4 IFO Beam Steering Reliability

Mean Time Between Failures (MTBF) of the IFO beam steering is the lifetime of the PZT tilt platform, which is expected to be the life of the IFO.

3.1.8.3 IFO Beam Steering Isolator Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.1.8.4 IFO Beam Steering Qualification

Test and acceptance criteria. TBD

3.2 Optical Sensing Beams

3.2.1 Initial Pointing Beam

The initial pointing beam shall monitor the angular alignment of the main input beam into the IFO, with accuracy sufficient to acquire the initial alignment of the COC mirrors.

3.2.1.1 Introduction

The initial pointing beam is sampled from the main IFO beam with a beam splitter, after the pointing by the IFO steering mirrors has occurred. The initial pointing beam is detected, after it exits from the end chamber, with an angle-sensing quad photodiode system, identical to that used for the optical lever beams.

The launch point of the initial pointing beam is shown in Figure 14: IFO beam steering. The steering mirrors and angle sensor for the initial pointing beam are shown in Figure 15: Initial pointing beam angle sensor.

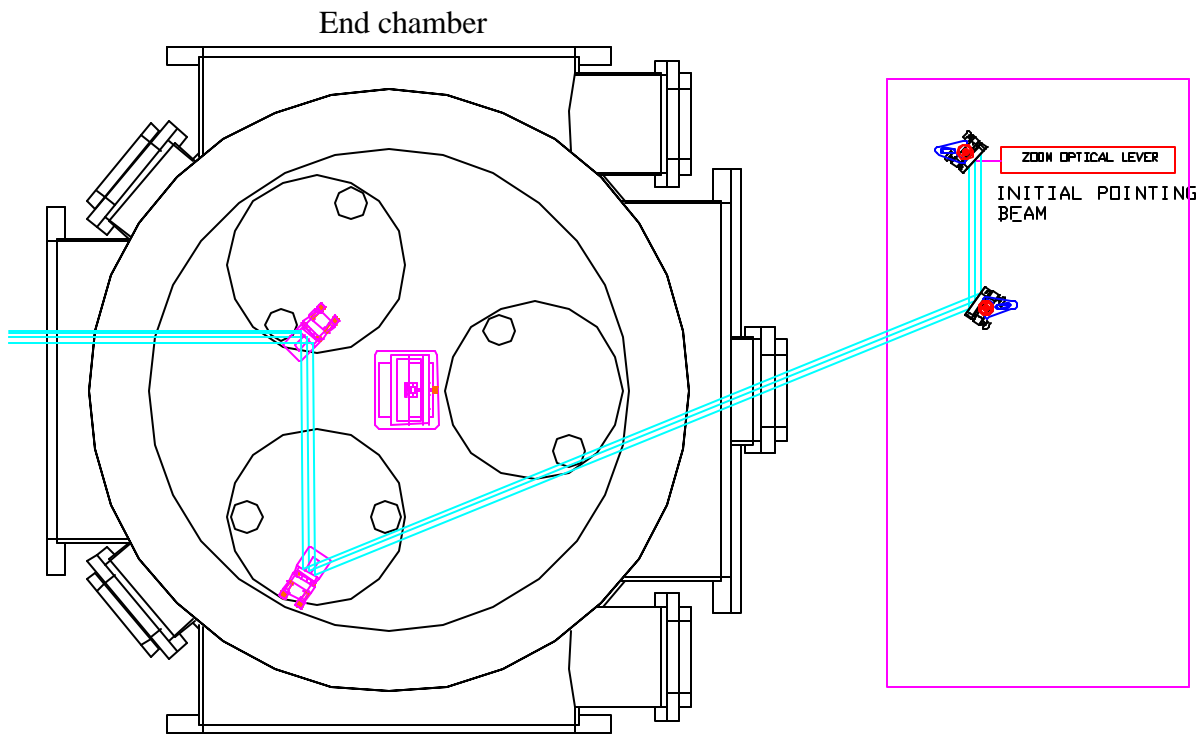


Figure 15: Initial pointing beam angle sensor

3.2.1.2 Initial Pointing Beam Characteristics

3.2.1.2.1 Initial Pointing Beam Performance Characteristics

Table 23: Initial Pointing Beam performance characteristics

Parameter	Requirement	Actual
Pointing angle	Same as IFO beam	Same as IFO beam
Angle resolution	0.00001 rad	< 0.00001 rad
Sensor bandwidth		> 100 kHz
Main beam sample fraction	< 1 %	0.25 %

3.2.1.2.2 Initial Pointing Beam Physical Characteristics

Table 24: Initial Pointing Beam physical characteristics

Parameter	Requirement	Actual
Beam diameter		100ppm main beam
Angle sensor		Quad photodiode
Beam splitter:		
Diameter		25.4 mm
Thickness		6.4 mm
Wedge		30 arc min

3.2.1.2.3 Initial Pointing Beam Interface Definitions

3.2.1.2.3.1 Interfaces to other LIGO detector subsystems

3.2.1.2.3.1.1 Mechanical Interfaces

The initial pointing beam beamsplitter is mounted to the optical table on the BS chamber. The angle sensor is mounted on the ETM transmission monitor table at the end of the IFO arm.

3.2.1.2.3.1.2 Electrical Interfaces

The quad position sensor has an interface to the CDS mirror control system.

3.2.1.2.3.1.3 Optical Interfaces

The initial pointing beam beamsplitter is centered on the main IFO beam. The beam exits through the output window of the end chamber.

3.2.1.2.4 Initial Pointing Beam Reliability

Mean Time Between Failures (MTBF) is expected to be the lifetime of the PSL laser.

3.2.1.2.5 Initial Pointing Beam Maintainability

Mean Time To Repair (MTTR) is expected to be the same as the PSL laser.

3.2.1.3 Initial Pointing Beam Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.1.4 Initial Pointing Beam Qualification

Test and acceptance criteria. TBD

3.2.2 IMC Reflected Beam

The IMC Reflected Beam shall provide angle and position wave-front signals for controlling the alignment of the main IFO input beam into the IMC. It shall measure the RF frequency of the IMC input beam. It shall provide a video image of reflected IMC beam cross-section.

The IMC Reflected Beam sensors shall be protected from excessive optical power by a light-actuated EO shutter.

3.2.2.1 Introduction

The IMC reflected beam detection system contains the following elements: an electrically-actuated mechanical beam block, a fast acting EO beam shutter to protect the sensors from excessive light levels, a photodiode to monitor the power reflected from the input mode cleaner, two quad photodiodes for wave front sensing, an RF photodiode for mode cleaner length control, a video camera to monitor the beam mode shape.

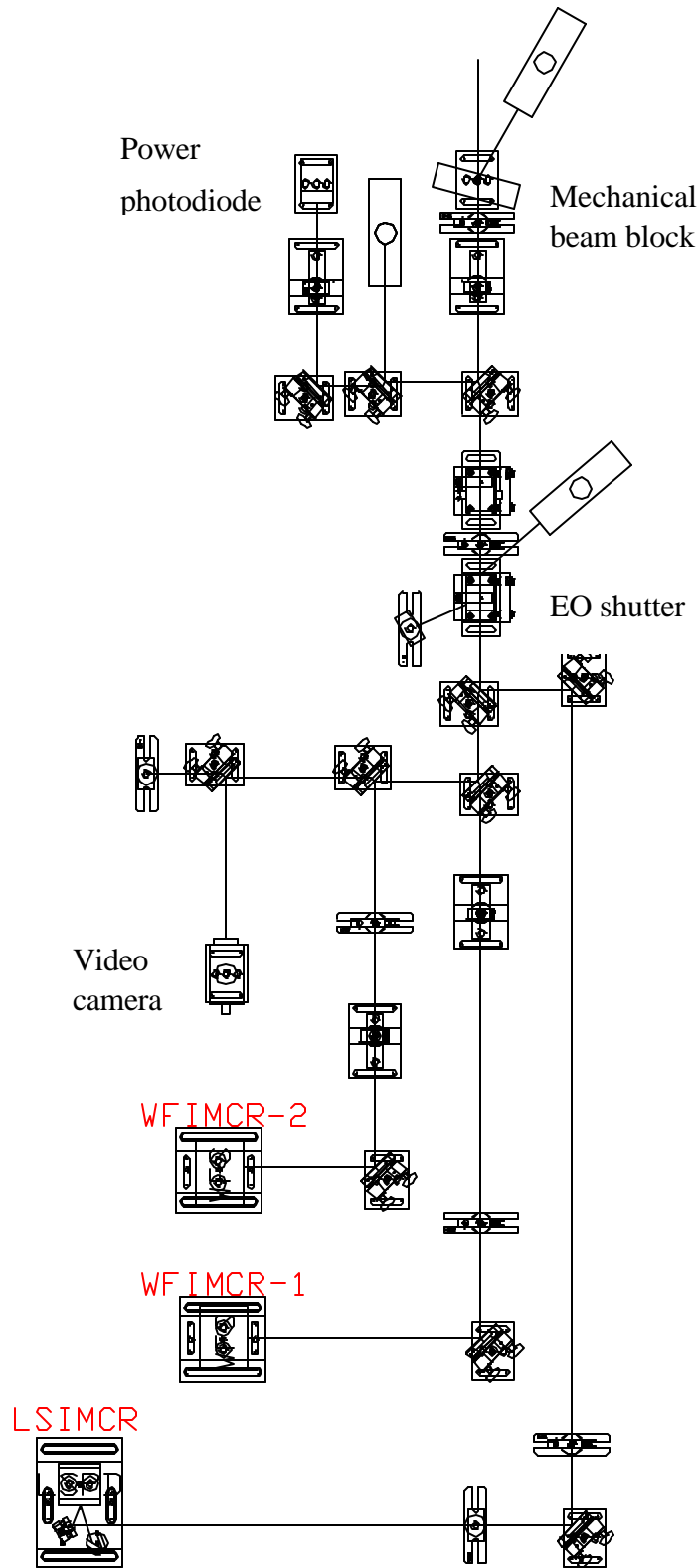


Figure 16: Input mode cleaner reflected beam sensing system

3.2.2.2 IMC Reflected Beam Characteristics

3.2.2.2.1 IMC Reflected Beam Performance Characteristics

Table 25: IMC Reflected Beam Performance Characteristics

Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.5 wave @ 1064 nm
Main beam sample fraction		0.6 %
WFS1, Guoy phase 1	Quad photodiode, 29.5 MHz	Quad photodiode, 29.5 MHz
WFS2, Guoy phase 2	Quad photodiode, 29.5 MHz	Quad photodiode, 29.5 MHz
LS, RF photodiode	29.5 MHz	29.5 MHz
Fast beam shutter	Yes	EO shutter
Mechanical beam block	Yes	Uniblitz
Video camera	Yes	Watek
Reflected power monitor	Yes	

3.2.2.2.2 IMC Reflected Beam Physical Characteristics

Table 26: IMC Reflected Beam Physical Characteristics

Parameter	Requirement	Actual
Beam diameter		13 mm

3.2.2.2.3 IMC Reflected Beam Interface Definitions

3.2.2.2.3.1 Interfaces to other LIGO detector subsystems

3.2.2.2.3.1.1 Mechanical Interfaces

The IMC Reflected Beam pick-off mirror is mounted to the optical table on the input chamber. The WFS sensor is mounted on the IMC_R external optical table.

3.2.2.2.3.1.2 Electrical Interfaces

The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, and video monitor have electrical interfaces to CDS.

3.2.2.2.3.1.3 Optical Interfaces

The IMC Reflected Beam pick-off mirror steers the IMC reflected beam through the output window of the output chamber.

3.2.2.2.3.1.4 Stay Clear Zones

3.2.2.2.3.2 *Interfaces external to LIGO detector subsystems*

3.2.2.2.3.2.1 Mechanical Interfaces

3.2.2.2.3.2.2 Electrical Interfaces

3.2.2.2.3.2.3 Stay Clear Zones

3.2.2.2.4 IMC Reflected Beam Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.2.2.5 IMC Reflected Beam Interchangeability

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.2.3 IMC Reflected Beam Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.2.4 IMC Reflected Beam Qualification

Test and acceptance criteria. TBD

3.2.3 IMC Transmitted Beam

The IMC Transmitted Beam shall provide PSL intensity stabilization photodiode signals. It shall measure the RF frequency of the IMC input beam, shall provide an RFAM RF signal to determine amount of residual RFAM at the modulated side band frequencies, shall monitor the power transmitted through the input mode cleaner, shall monitor the beam mode shape, and shall measure the RF sidebands.

3.2.3.1 Introduction

The input mode cleaner transmitted beam detection system contains the following elements: an electrically actuated mechanical beam block, PSL intensity stabilization photodiode, RFAM RF, an optical power photodiode, a video camera, and an optical spectrum analyzer to monitor the RF sidebands.

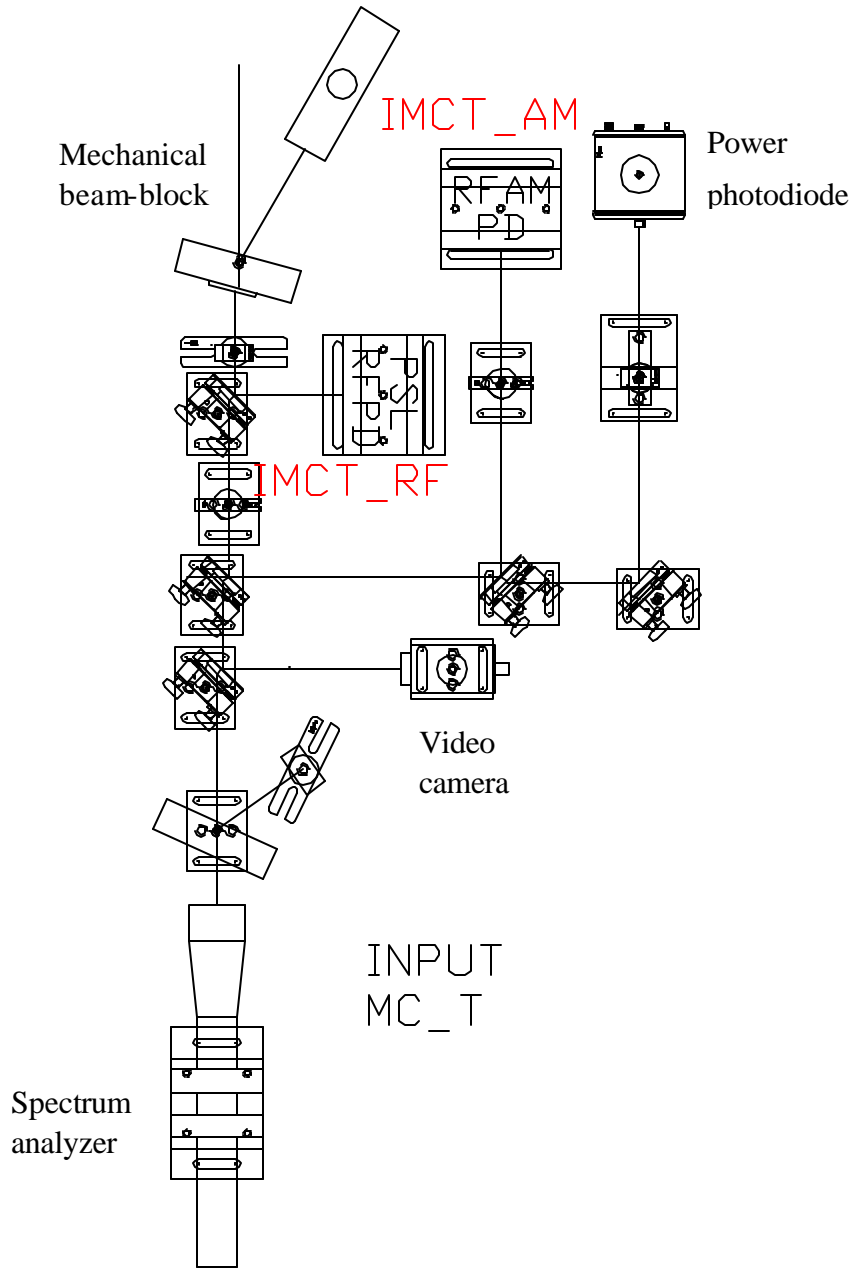


Figure 17: Input mode cleaner transmitted beam

3.2.3.2 IMC Transmitted Beam Characteristics

3.2.3.2.1 IMC Transmitted Beam Performance Characteristics

Table 27: IMC transmitted beam performance characteristics

Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.5 wave @ 1064 nm
Main beam sample fraction	0.6 %	0.6 %
RFAM RF photodetector	TBD	TBD
PSL intensity stabilization, RF photodetector	TBD	TBD
Transmitted power photodetector	Yes	
Optical Spectrum analyzer	Yes	Coherent
Fast beam shutter	Yes	EO shutter
Mechanical beam block	Yes	Uniblitz
Video camera	yes	Watek

3.2.3.2.2 IMC Transmitted Beam Physical Characteristics

Table 28: IMC transmitted beam physical characteristics

Parameter	Requirement	Actual
Beam diameter		13 mm
Beam splitter:		
Diameter		25.4 mm
Thickness		6.4 mm
Wedge		30 arc min

3.2.3.2.3 IMC Transmitted Beam Interface Definitions

3.2.3.2.3.1 Interfaces to other LIGO detector subsystems

3.2.3.2.3.1.1 Mechanical Interfaces

The IMC Transmitted Beam beamsplitter is mounted to the optical table on the input chamber. The RFAM photodetector is mounted on the IMC_R external optical table.

3.2.3.2.3.1.2 Electrical Interfaces

The mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor have electrical interfaces to CDS.

3.2.3.2.3.1.3 Optical Interfaces

The IMC Transmitted Beam beamsplitter and pick-off mirror steer the IMC transmitted beam through the output window of the output chamber.

3.2.3.2.3.1.4 Stay Clear Zones

3.2.3.2.3.2 *Interfaces external to LIGO detector subsystems*

3.2.3.2.3.2.1 Mechanical Interfaces

3.2.3.2.3.2.2 Electrical Interfaces

3.2.3.2.3.2.3 Stay Clear Zones

3.2.3.2.4 **IMC Transmitted Beam Reliability**

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.3.2.5 **IMC Transmitted Beam Interchangeability**

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.3.3 **IMC Transmitted Beam Precedence**

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.3.4 **IMC Transmitted Beam Qualification**

Test and acceptance criteria. TBD

3.2.4 **Symmetric Port Signal**

The Symmetric Port Signal (SPS) shall provide an angle sensing signal and a length sensing signal to control the angular and length alignment of the COC mirrors; it shall provide a bull's eye photodetector for IFO input beam alignment diagnostics. It shall provide a video image of the reflected IFO beam cross-section. It shall provide an optical spectrum analyzer to determine the frequency spectrum. The SPS sensors shall be protected from excessive optical power by a light-actuated EO shutter

3.2.4.1 Introduction

The SPS beam detection system contains the following elements: an electrically actuated mechanical beam block, a fast acting EO shutter, an optical power monitor, a quad photodiode for wave front sensing, two RF photodiodes for mode cleaner length control, a video camera, an optical spectrum, and bull’s eye photodetectors.

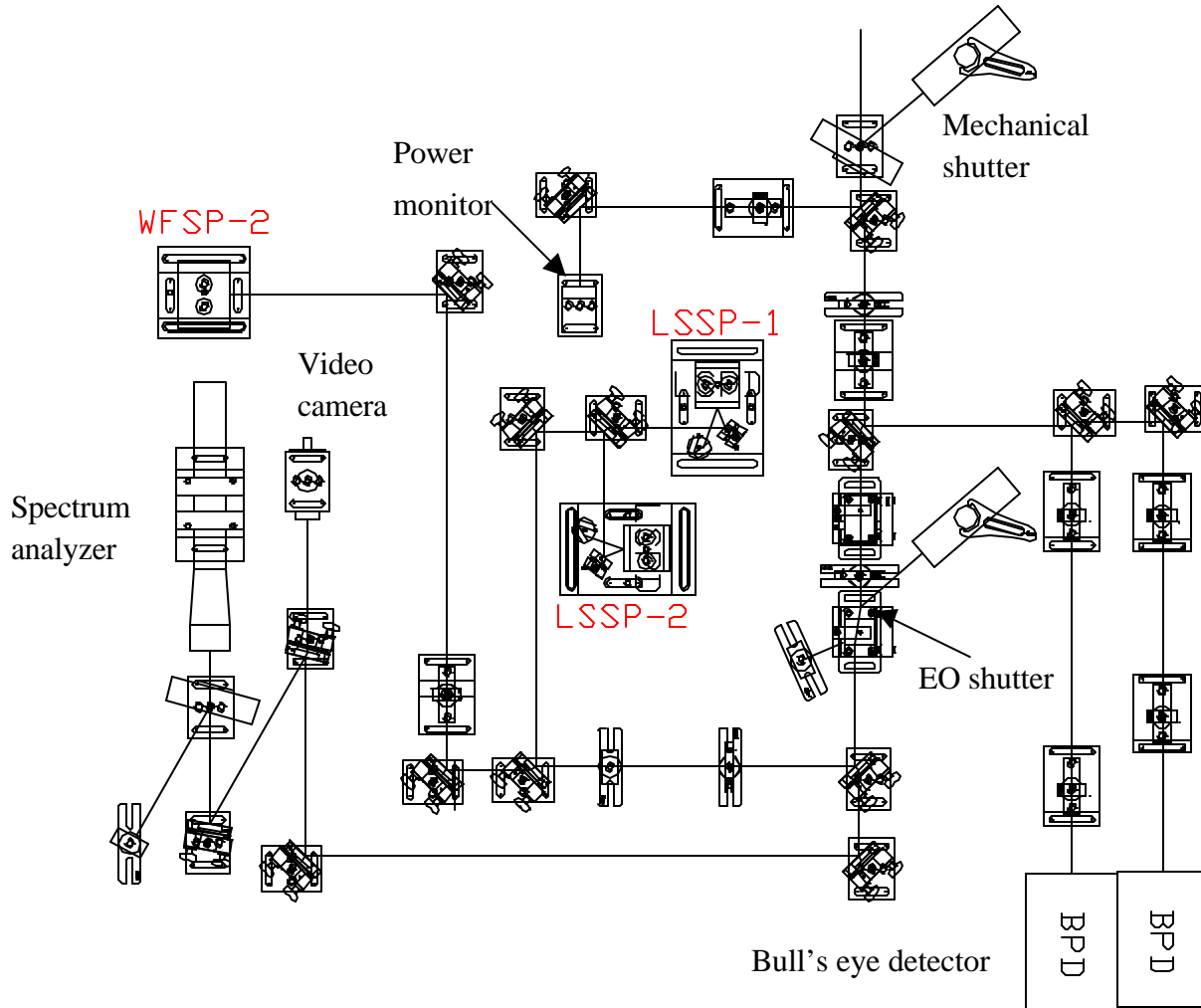


Figure 18: SPS sensing system

3.2.4.2 Symmetric Port Signal Characteristics

3.2.4.2.1 Symmetric Port Signal Performance Characteristics

Table 29: Symmetric port signal performance characteristics

Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.3 wave @ 1064 nm
Symmetric port power ratio	0.01	0.01
WFSP-2 , frequency	Quad photodiode, TBD MHz	Quad photodiode, TBD MHz
LSSP-1, frequency	35.5 MHz	35.5 MHz
LSSP-2, frequency	141.9 MHz	141.9 MHz
Bull's eye photodetector		TBD
Fast beam shutter	Yes	EO shutter
Mechanical beam block	Yes	Uniblitz

3.2.4.2.2 Symmetric Port Signal Physical Characteristics

Table 30: Symmetric port signal physical characteristics

Parameter	Requirement	Actual
Beam diameter		11 mm

3.2.4.2.3 Symmetric Port Signal Interface Definitions

3.2.4.2.3.1 Interfaces to other LIGO detector subsystems

3.2.4.2.3.1.1 Mechanical Interfaces

The Symmetric Port Signal is reflected from the input Faraday Isolator input Brewster's angle polarizer mounted to the optical table in the input chamber. The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor are mounted on the SPS external optical table.

3.2.4.2.3.1.2 Electrical Interfaces

The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor have electrical interfaces to CDS.

3.2.4.2.3.1.3 Optical Interfaces

The Symmetric Port Signal pick-off mirror steers the IFO reflected beam through the output window of the output chamber.

3.2.4.2.3.1.4 Stay Clear Zones

3.2.4.2.4 Symmetric Port Signal Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.4.2.5 Symmetric Port Signal Interchangeability

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.4.2.6 Symmetric Port Signal Human Engineering

3.2.4.3 Symmetric Port Signal Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design.

3.2.4.4 Symmetric Port Signal Qualification

Test and acceptance criteria.

3.2.5 ITM_x, ITM_y, and BS Pickoff Beams

The ITM_x, ITM_y, and BS Pickoff Beams shall provide an angle sensing signal and a length sensing signal to control the angular and length alignment of the COC mirrors; it shall provide a video image of the PO beam cross-section. It shall provide an optical spectrum analyzer to determine the frequency spectrum.

3.2.5.1 Introduction

The ITM_x, ITM_y, and BS Pickoff beam detection system contains the following elements: quad photodiodes for wave front sensing, RF photodiodes for COC length control, a video camera, and an optical power monitor.

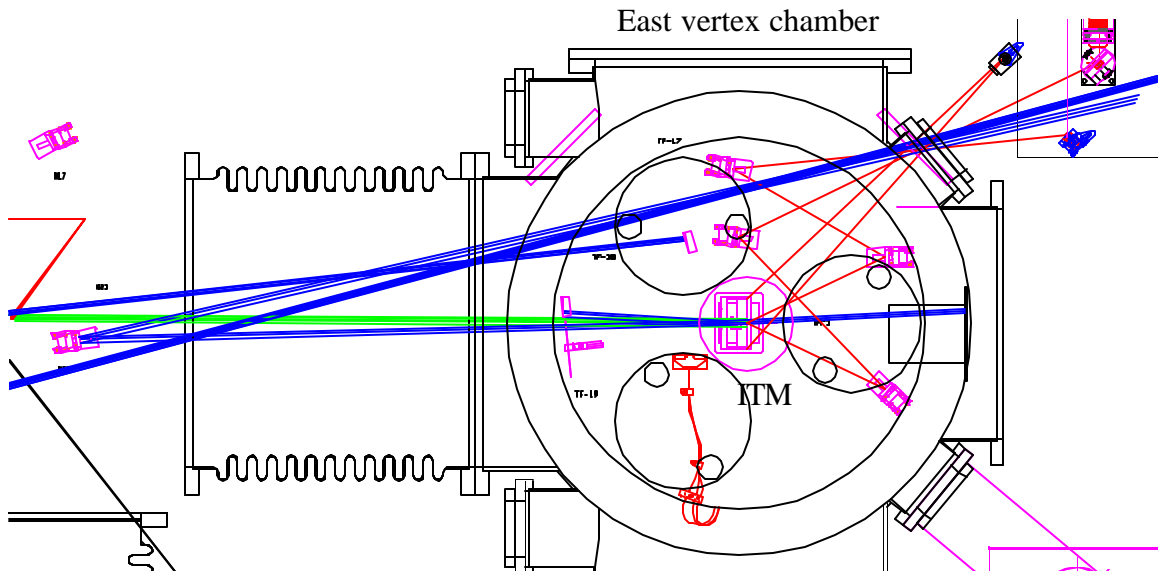


Figure 19: ITMx, ITMy pick-off beam

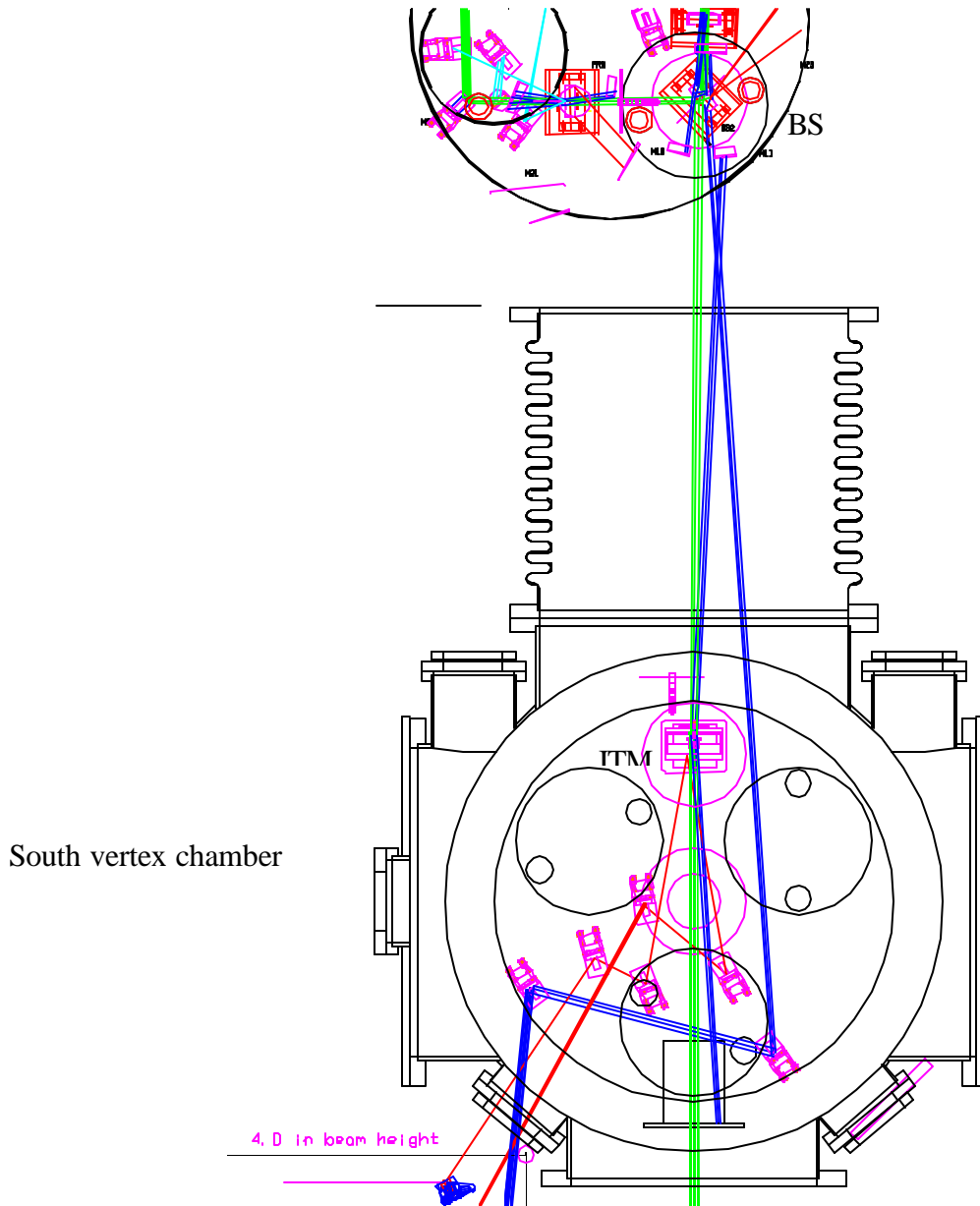


Figure 20: BS pick-off beam

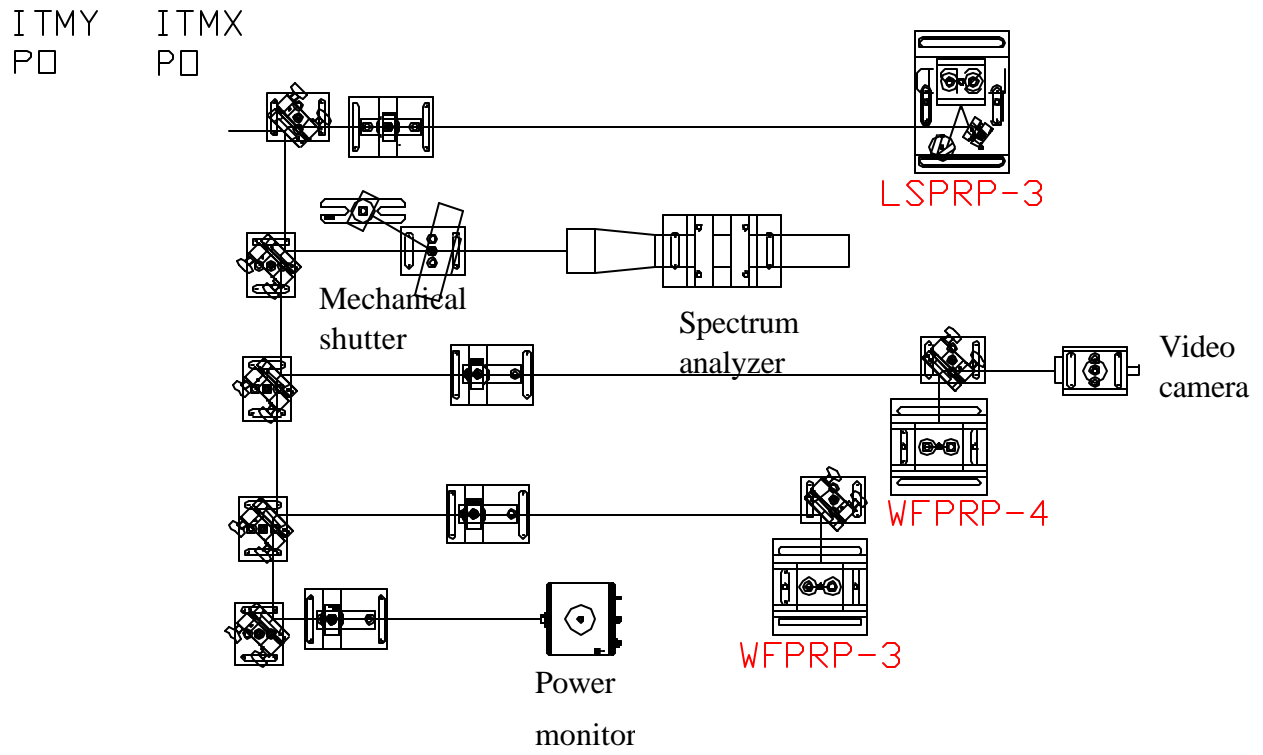


Figure 21 : ITM pick-off beam sensing system

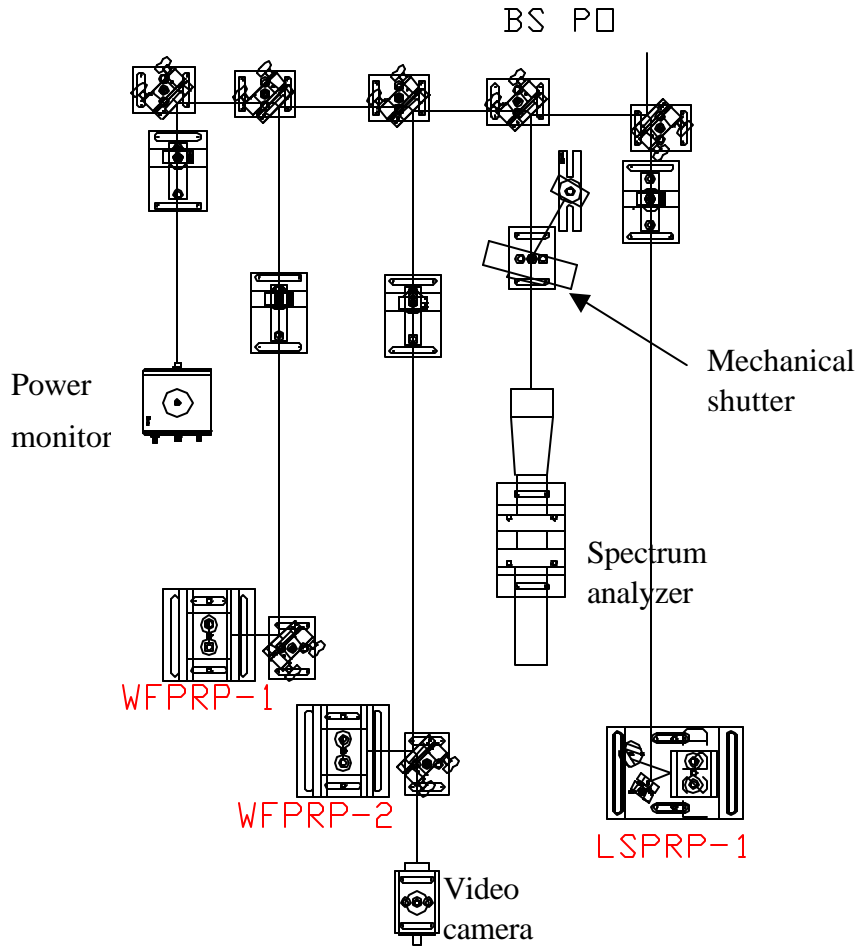


Figure 22: BS pick-off beam sensing system

3.2.5.2 ITM_x, ITM_y, and BS Pickoff Beams Characteristics

3.2.5.2.1 ITM_x, ITM_y, and BS Pickoff Beams Performance Characteristics

Table 31: ITM_x, ITM_y, and BS Pickoff Beams Performance Characteristics

Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.3 wave @ 1064 nm
Pick-off power ratio	0.0005	0.0005
WFSPPR, Guoy phase 1	Quad photodiode, 141.9 MHz	Quad photodiode, 141.9 MHz
WFSPPR, Guoy phase 2	Quad photodiode, 141.9 MHz	Quad photodiode, 141.9 MHz
LSSPRP-1, frequency	141.9 MHz	141.9 MHz

3.2.5.2.2 ITM_x, ITM_y, and BS Pickoff Beams Physical Characteristics

Table 32: ITM_x, ITM_y, and BS Pickoff Beams Physical Characteristics

Parameter	Requirement	Actual
Beam diameter		13 mm

3.2.5.2.3 ITM_x, ITM_y, and BS Pickoff Beams Interface Definitions

3.2.5.2.3.1 Interfaces to other LIGO detector subsystems

3.2.5.2.3.1.1 Mechanical Interfaces

The ITM_x and ITM_y pick-off beams are reflected from the AR surface of the ITM_x and ITM_y mirrors; the BS pickoff beam is reflected from the AR surface of the BS after an internal reflection. The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor are mounted on the external optical table.

3.2.5.2.3.1.2 Electrical Interfaces

The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor have electrical interfaces to CDS.

3.2.5.2.3.1.3 Optical Interfaces

The ITM_x, ITM_y, and BS Pickoff Beams pick-off mirrors steers the PO beams through the output window of the vertex chambers.

3.2.5.2.3.1.4 Stay Clear Zones

The ITM_x, ITM_y, and BS Pickoff Beams will stay clear of the main IFO beam.

3.2.5.2.4 ITM_x, ITM_y, and BS Pickoff Beams Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.5.2.5 ITM_x, ITM_y, and BS Pickoff Beams Interchangeability

Specify the level at which components shall be interchangeable or replaceable.

3.2.5.3 ITM_x, ITM_y, and BS Pickoff Beams Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.5.4 ITM_x, ITM_y, and BS Pickoff Beams Qualification

Test and acceptance criteria. TBD

3.2.6 AP1 Output beam

The AP1 beam shall have a Faraday isolator to attenuate the reflected and scattered light into the IFO; it shall provide angle sensing signal and length sensing signal to control the angular and length alignment of the COC mirrors. It shall provide a video image of the AP1 beam cross-section. It shall provide an optical spectrum analyzer to determine the frequency spectrum. A focus lens shall be provided to minimize the beam size at the sensors. The AP1 sensors shall be protected from excessive optical power by a light-actuated EO shutter.

3.2.6.1 Introduction

The AP1 beam detection system contains the following elements: a Faraday isolator, a focus lens, an electrically actuated mechanical beam block, a fast acting EO beam shutter, an optical power monitor, quad photodiodes for wave front sensing, RF photodiodes for mode cleaner length control, a video camera, an optical spectrum.

3.2.6.2 Output Faraday Isolator

3.2.6.2.1 Output Faraday Isolator Characteristics

3.2.6.2.1.1 Output Faraday Isolator Performance Characteristics

Table 33: Output Faraday Isolator Performance Characteristics

Parameter	Requirement	Actual
Wavelength	1064 nm	
Transmissivity across clear aperture		> 95%
Extinction ratio	1000:1	1000:1

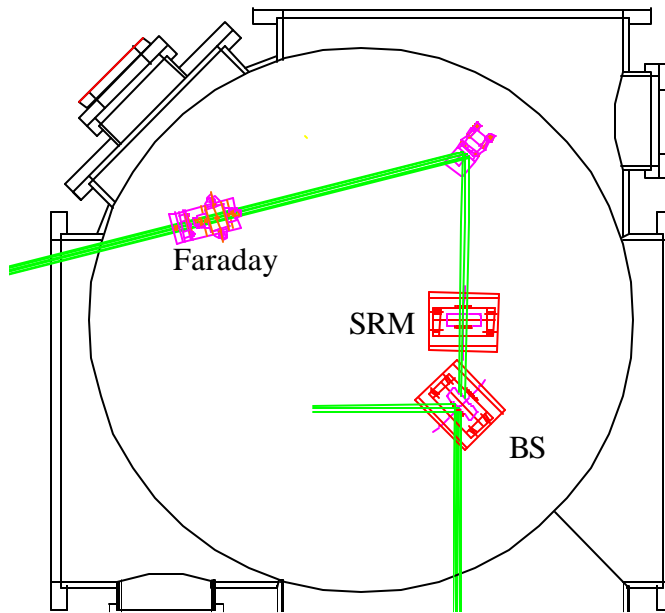


Figure 23: Output Faraday Isolator

3.2.6.2.1.2 Output Faraday Isolator Physical Characteristics

Table 34: Output Faraday Isolator Physical Characteristics

Parameter	Requirement	Actual
Clear aperture	13 mm	20 mm
Faraday material		TGG

3.2.6.2.1.3 Output Faraday Isolator Interface Definitions

3.2.6.2.1.3.1 Interfaces to other LIGO detector subsystems

3.2.6.2.1.3.1.1 Mechanical Interfaces

The output Faraday Isolator will mount on the BS chamber optical table.

3.2.6.2.1.3.1.2 Optical Interfaces

The output Faraday Isolator is centered on the main beam exiting from the SR mirror.

3.2.6.2.1.3.1.3 Stay Clear Zones

The optical aperture of the output Faraday Isolator shall not vignette the output beam more than 100 ppm.

3.2.6.2.1.4 Output Faraday Isolator Reliability

Mean Time Between Failures (MTBF) is equal to the life of the interferometer.

3.2.6.2.1.5 Output Faraday Isolator Maintainability

Mean Time To Repair (MTTR) is equal to the life of the interferometer.

3.2.6.2.1.6 Output Faraday Isolator Interchangeability

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.6.2.2 Output Faraday Isolator Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.6.2.3 Output Faraday Isolator Qualification

Test and acceptance criteria. TBD

3.2.6.3 AP1 Focus Lens

3.2.6.3.1 AP1 Focus Lens Characteristics

3.2.6.3.1.1 AP1 Focus Lens Performance Characteristics

Table 35: AP1 Focus Lens Performance Characteristics

Parameter	Requirement	Actual
Wavelength	1064 nm	
Transmissivity across clear aperture		> 99%
Wavefront distortion		< 1/10 wave @ 1064 nm
Spot diameter at ISC input, 100 ppm		15

3.2.6.3.1.2 AP1 Focus Lens Physical Characteristics

Table 36: AP1 Focus Lens Physical Characteristics

Parameter	Requirement	Actual
Clear aperture	13 mm	25 mm

3.2.6.3.1.3 AP1 Focus Lens Interface Definitions

3.2.6.3.1.3.1 Interfaces to other LIGO detector subsystems

3.2.6.3.1.3.1.1 Mechanical Interfaces

The AP1 focus lens is mounted on the optical table inside the output chamber.

3.2.6.3.1.3.1.2 *Optical Interfaces*

The AP1 focus lens is on the optical centerline of the AP1 output beam.

3.2.6.3.1.4 *AP1 Focus Lens Reliability*

Mean Time Between Failures (MTBF) is expected to be the life of the IFO.

3.2.6.3.1.5 *AP1 Focus Lens Interchangeability*

This is a commercial catalog item and is interchangeable with the same part number.

3.2.6.3.2 AP1 Focus Lens Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.6.3.3 AP1 Focus Lens Qualification

Test and acceptance criteria. TBD

3.2.6.4 AP1 ISC System

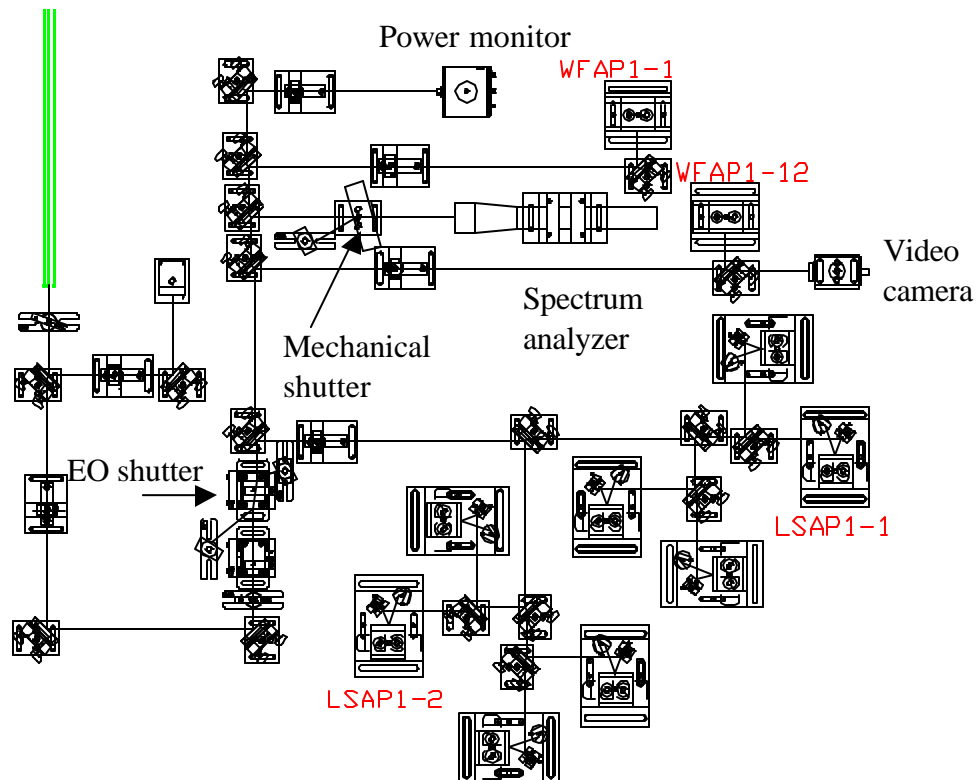


Figure 24: AP1 ISC System

3.2.6.4.1 AP1 ISC System Characteristics

3.2.6.4.1.1 AP1 ISC System Performance Characteristics

Table 37: AP1 ISC System Performance Characteristics

Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.3 wave @ 1064 nm
Output power ratio	0.01	0.01
WFAP-1, Guoy phase 1	Quad photodiode, TBD MHz	Quad photodiode, TBD MHz
WFAP-2, Guoy phase 2	Quad photodiode, TBD MHz	Quad photodiode, TBD MHz
LSAP-1, frequency	177.3 MHz	177.3 MHz
LSAP-2, double demodulation	141.9 MHz, 212.8 MHz	35.5 MHz
Fast beam shutter	Yes	EO shutter
Mechanical beam block	Yes	Uniblitz
Video camera	Yes	Watek
Optical spectrum analyzer	Yes	Coherent

3.2.6.4.1.2 AP1 ISC System Physical Characteristics

Table 38: AP1 ISC System Physical Characteristics

Parameter	Requirement	Actual
Beam diameter		13 mm

3.2.6.4.1.3 AP1 ISC System Interface Definitions

3.2.6.4.1.3.1 Interfaces to other LIGO detector subsystems

3.2.6.4.1.3.1.1 Mechanical Interfaces

The AP1 ISC System has two steering mirrors mounted on the optical table inside the output chamber. The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor are mounted on the external AP1 ISC System optical table.

3.2.6.4.1.3.2 Electrical Interfaces

The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, wavelength analyzer, and video monitor have electrical interfaces to CDS.

3.2.6.4.1.3.3 Optical Interfaces

The AP1 ISC System mirrors steers the AP1 ISC beam through the output window of the output chamber.

3.2.6.4.1.4 AP1 ISC System Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.6.4.2 AP1 ISC System Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design.

3.2.6.4.3 AP1 ISC System Qualification

Test and acceptance criteria.

3.2.7 OMC Reflected Beam

The OMC Reflected Beam shall provide angle-sensing signals to control the angular alignment of the OMC steering mirrors; it shall provide length-sensing signal to control the length of the OMC. It shall provide a video image of the reflected OMC beam cross-section. The OMC sensors shall be protected from excessive optical power by a light-actuated EO shutter.

3.2.7.1 Introduction

The OMC beam detection system contains the following elements: a beam expanding telescope with steering mirrors to control the spot size and location at the detection table, an electrically-actuated mechanical beam block, a fast acting EO beam shutter, an optical power monitor, quad photodiodes for wave front sensing, RF photodiodes for mode cleaner length control, a video camera.

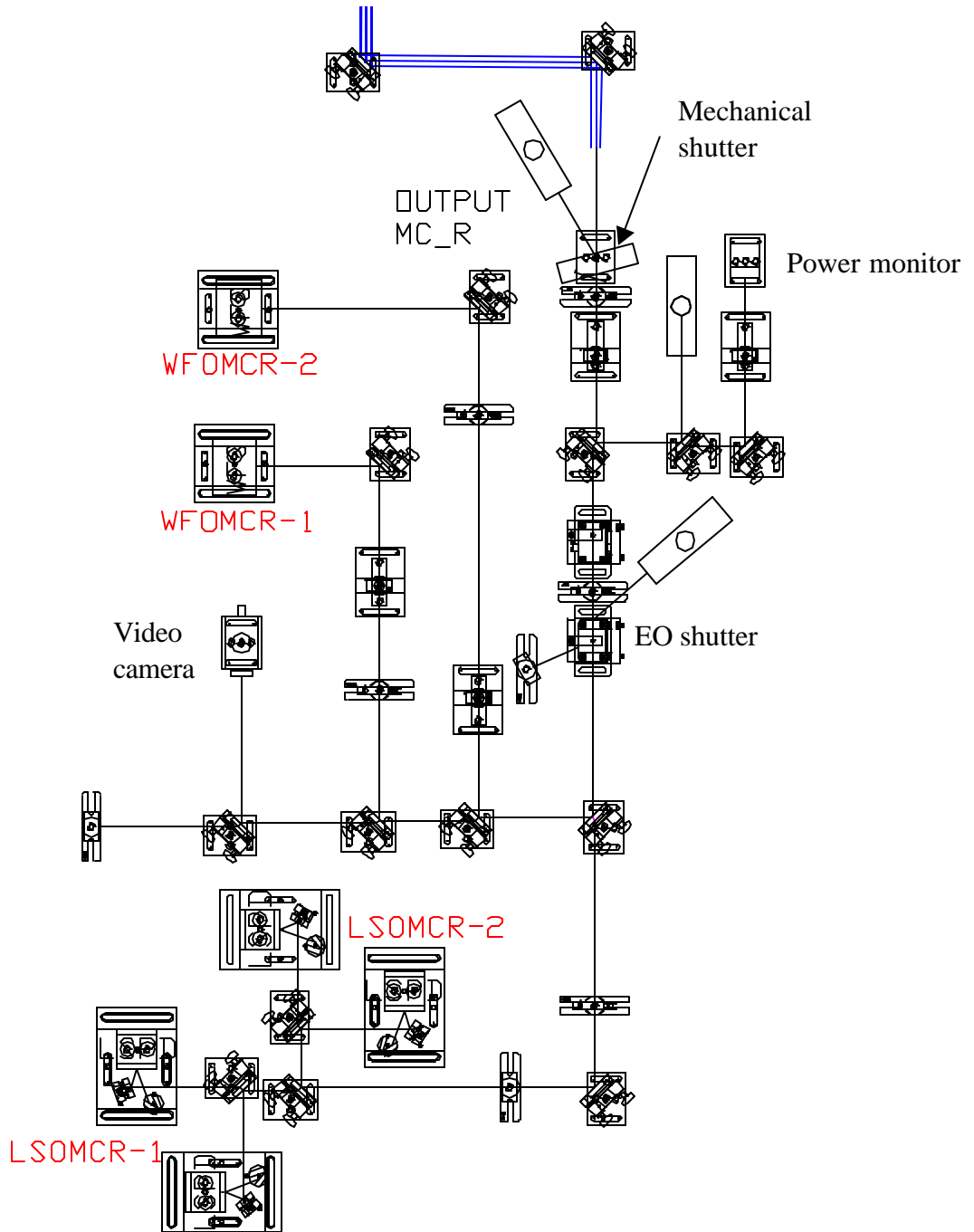


Figure 25: OMC reflected beam sensing system

3.2.7.2 OMC Reflected Beam Characteristics

3.2.7.2.1 OMC Reflected Beam Performance Characteristics

Table 39: OMC Reflected Beam Performance Characteristics

Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.3 wave @ 1064 nm
Main beam sample fraction	0.01	0.01
WFS1, Guoy phase 1	Quad photodiode, 177.3 MHz	Quad photodiode, 177.3 MHz
WFS2, Guoy phase 2	Quad photodiode, 177.3 MHz	Quad photodiode, 177.3 MHz
LS, RF photodiode	177.3 MHz	177.3 MHz
Fast beam shutter	Yes	EO shutter
Mechanical beam block	Yes	Uniblitz
Video camera	Yes	Watek
Reflected power monitor photodiode	yes	

3.2.7.2.2 OMC Reflected Beam Physical Characteristics

Table 40: OMC Reflected Beam Physical Characteristics

Parameter	Requirement	Actual
Beam diameter		13 mm

3.2.7.2.3 OMC Reflected Beam Interface Definitions

3.2.7.2.3.1 Interfaces to other LIGO detector subsystems

3.2.7.2.3.1.1 Mechanical Interfaces

The OMC reflected beam detection system mounts to an external optical table at a 4.00 in beam height. The beam expanding telescope and two steering mirrors are mounted to the optical table in the output chamber. Another steering mirror is mounted to the external optical table adjacent to the output chamber.

3.2.7.2.3.1.2 Electrical Interfaces

The wavefront sensor, length sensor, mechanical shutter, EO shutter, power photodetector, and video camera have electrical interfaces to CDS.

3.2.7.2.3.1.3 Optical Interfaces

The first steering mirror inside the output chamber is centered on the OMC reflected beam.

3.2.7.2.3.1.4 Stay Clear Zones

3.2.7.2.4 OMC Reflected Beam Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.7.2.5 OMC Reflected Beam Interchangeability

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.7.3 OMC Reflected Beam Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.7.4 OMC Reflected Beam Qualification

Test and acceptance criteria. TBD

3.2.8 ETM_x & ETM_y Transmission Monitor

The ETM transmission monitor shall monitor the position of the IFO beam on the ETM mirror and shall provide an electronic position signal for the IFO COC mirror alignment control.

3.2.8.1 Introduction

The ETM transmission monitor consists of the following elements: a beam splitter power attenuator mounted to the optical table inside the end chamber, two steering mirrors, a focusing telescope, a beam splitter, and a quad photodiode beam position sensor mounted at a 4 in beam height on the external optical table adjacent to the end chamber.

3.2.8.2 ETM_x & ETM_y Transmission Monitor Characteristics

3.2.8.2.1 ETM_x & ETM_y Transmission Monitor Performance Characteristics

Table 41: Summary of ETM transmission monitor performance characteristics

Parameter	Requirement	Actual
Output power ratio	0.01	0.01
Position transfer ratio, mm/mm		-0.18
Beam position pointing resolution, mm	0.52	0.055
Beam splitter attenuation ratio	0.1	0.1

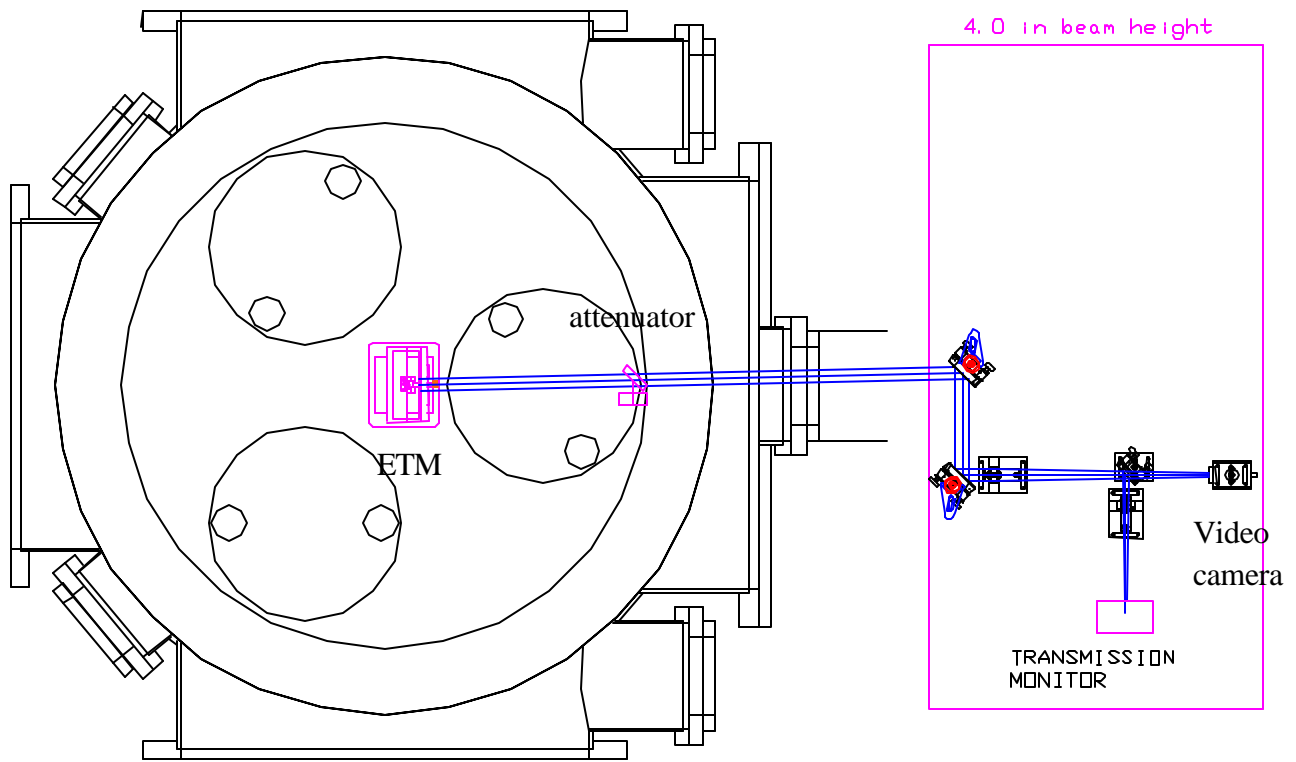


Figure 26: ETM transmission monitor

3.2.8.2.2 ETM_x & ETM_y Transmission Monitor Physical Characteristics

Table 42: ETM_x & ETM_y Transmission Monitor Physical Characteristics

Parameter	Requirement	Actual
Beam diameter		23 mm
Quad photodiode		

3.2.8.2.3 ETM_x & ETM_y Transmission Monitor Interface Definitions

3.2.8.2.3.1 Interfaces to other LIGO detector subsystems

3.2.8.2.3.1.1 Mechanical Interfaces

A beam splitter attenuator and beam dump will be mounted to the optics table in the end chamber. The ETM transmission monitor system is attached at a beam height of 4.00 in to an external optical table adjacent to the end chamber.

3.2.8.2.3.1.2 Electrical Interfaces

The quad photodiode position sensor has an electrical interface to CDS.

3.2.8.2.3.1.3 Optical Interfaces

The beam splitter attenuator of the ETM transmission monitor system is centered on the output beam transmitted through the ETM mirror.

3.2.8.2.3.1.4 Stay Clear Zones

3.2.8.2.4 ETMx & ETMy Transmission Monitor Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.8.3 ETMx & ETMy Transmission Monitor Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.8.4 ETMx & ETMy Transmission Monitor Qualification

Test and acceptance criteria. TBD

3.2.9 AP2 Output Beam

The AP2 Output Beam shall provide the signal that is used for gravity wave detection. It shall provide a video image of the AP2 Output beam cross-section. It shall provide an optical power monitor and a video camera. It shall provide a mode-matching telescope with beam steering into the mode cleaner, which reflects the RF sideband signals and all higher order modes. The AP2 sensors shall be protected from excessive optical power by a light-actuated EO shutter.

3.2.9.1 Introduction

The AP2 Output Beam detection system contains the following elements: a mode matching telescope, beam steering mirrors, a mode cleaner, a fast-acting EO beam shutter, an optical power monitor, a DC photodiode for GW signal detection, and a video camera.

3.2.9.2 OMC Mode Matching Telescope

The OMC Mode Matching Telescope shall transform the beam waist of the AP output beam into a new beam waist of the optimum size and location at the OMC.

3.2.9.2.1 Introduction

The output mode cleaner (OMC) mode-matching telescope is an off-axis parabolic reflective telescope of the Mersenne type. Its function is to transform the beam waist of the AP output beam

into a new beam waist of the optimum size and location at the OMC. An all-reflective design was chosen to minimize the light scattering and glint into the IFO.

The spacing between the primary and secondary mirror can be varied remotely for focusing, while under vacuum, by means of the electric Pico motor.

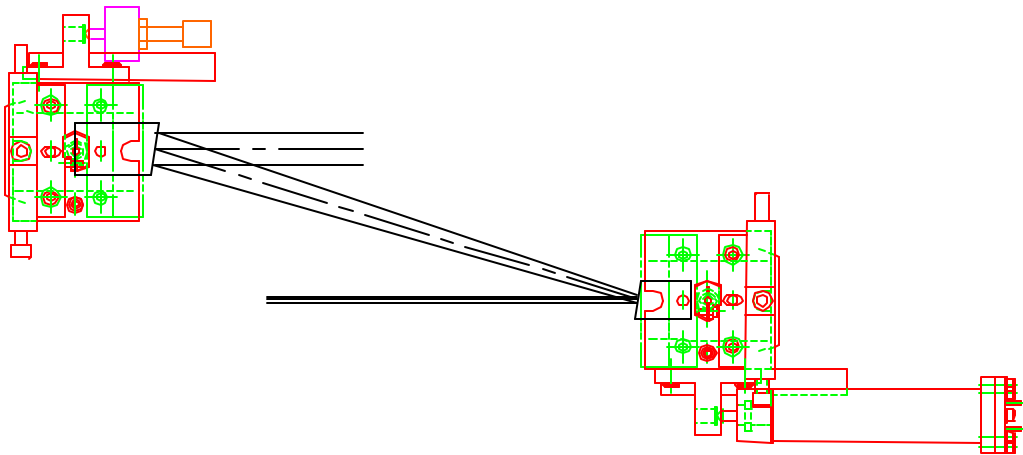


Figure 27: OMC mode matching telescope

3.2.9.2.2 OMC Mode Matching Telescope Characteristics

3.2.9.2.2.1 OMC Mode Matching Telescope Performance Characteristics

Table 43: OMC Mode Matching Telescope Performance Characteristics

Parameter	Requirement	Actual
Clear aperture M1, mm	13	25
Clear aperture M2, mm	3	19
Input beam waist radius, mm	3.027	3.027
Output beam waist radius, mm	0.37	0.369
Power coupling error	<0.05	< 0.0001
Wavefront distortion		<0.2
Transmissivity across clear aperture		> 99.8%, Dielectric coating, ion beam
Magnification	0.23	0.23

The telescope must be defocused for optimum mode matching. The mode matching power loss as a function of the defocus of the telescope is shown Figure 28: OMC mode matching telescope focus, for three secondary mirrors within a tolerance range of +/- 1.5 %.

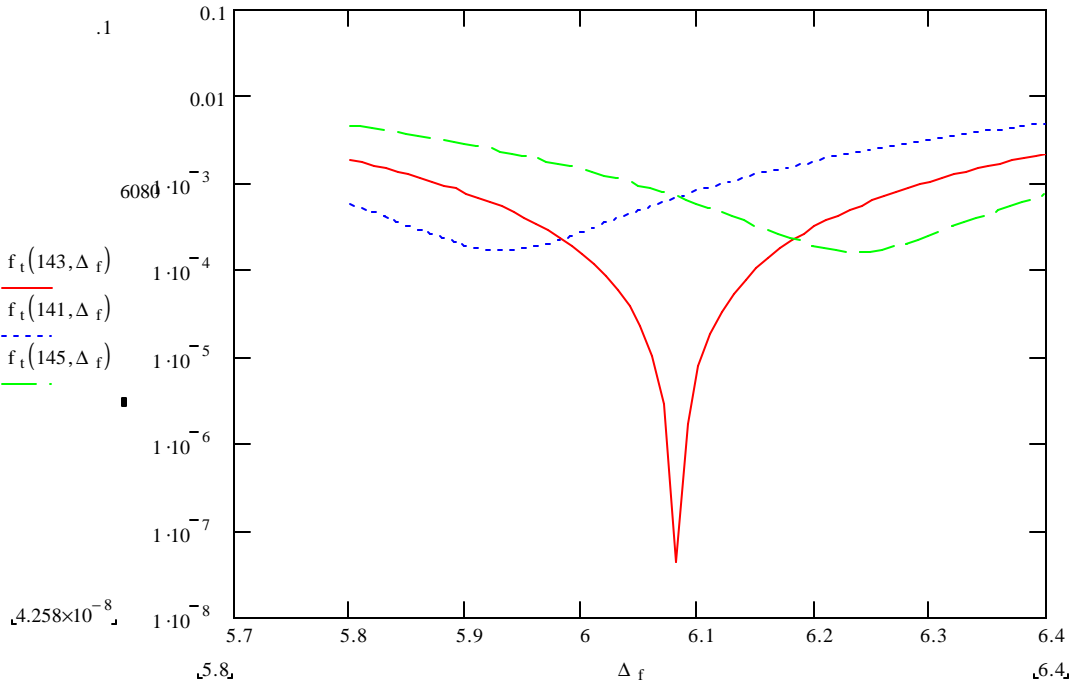


Figure 28: OMC mode matching telescope focus

3.2.9.2.2.2 OMC Mode Matching Telescope Physical Characteristics

Table 44: OMC Mode Matching Telescope Physical Characteristics

Parameter	Requirement	Actual
M1 focal length, mm		609.6
M2 focal length, mm		-143
Distance from SRM to M1, mm		3642
Distance to M2, mm		240.9
Substrate material		Zerodur

3.2.9.2.2.2.1 Optical Alignment

The telescope shall be pre-aligned before assembly into the IFO vacuum housing.

3.2.9.2.2.2.2 Resonant Frequency of Elements Mounted on the Optics Platform

The resonant frequencies and Q’s of the Telescope and accessory optics which are mounted to the optics platforms shall not induce excessive thermal-noise of the test mass.

3.2.9.2.2.3 IFO Mode Matching Telescope Interface Definitions

3.2.9.2.2.3.1 Interfaces to other LIGO detector subsystems

3.2.9.2.2.3.1.1 Mechanical Interfaces

The Telescope and associated optical train elements shall mount to the optical platform in the output chamber, without interfering with the COC mirror structures.

3.2.9.2.2.3.1.2 Electrical Interfaces

Table 45: Electrical Interfaces, OMC mode matching telescope

Parameter	Requirement	Actual
Pico motor focus		2 wires

3.2.9.2.2.3.1.3 Optical Interfaces

The Telescope shall provide a large enough field of view so that the AP beam will not vignette as a result of optical table motion after pump-down of the vacuum chambers.

3.2.9.2.2.3.1.4 Stay Clear Zones

All support components shall stay clear of the 1ppm diameter of the AP beam.

3.2.9.2.2.4 OMC Mode Matching Telescope Reliability

The telescope elements are passive and are expected to have a 100 % availability. The MTBF is expected to be equal to the life of the Pico motor.

3.2.9.2.2.5 OMC Mode Matching Telescope Maintainability

Spare components will be stocked for the replacement during installation of long lead-time items such as telescope mirrors and lenses.

3.2.9.2.3 OMC Mode Matching Telescope Precedence

The relative importance of the telescope subsystem requirements is as follows:

- 4) clear aperture through the telescope optical train
- 5) optical transmissivity through the telescope optical train
- 6) compatibility with COC elements

3.2.9.3 OMC Beam Steering

3.2.9.3.1 Introduction

The beam displacement and pointing angle of the beam into the OMC shall be steered remotely by means of PZT tilt mirrors, as shown in Figure 29: OMC beam steering

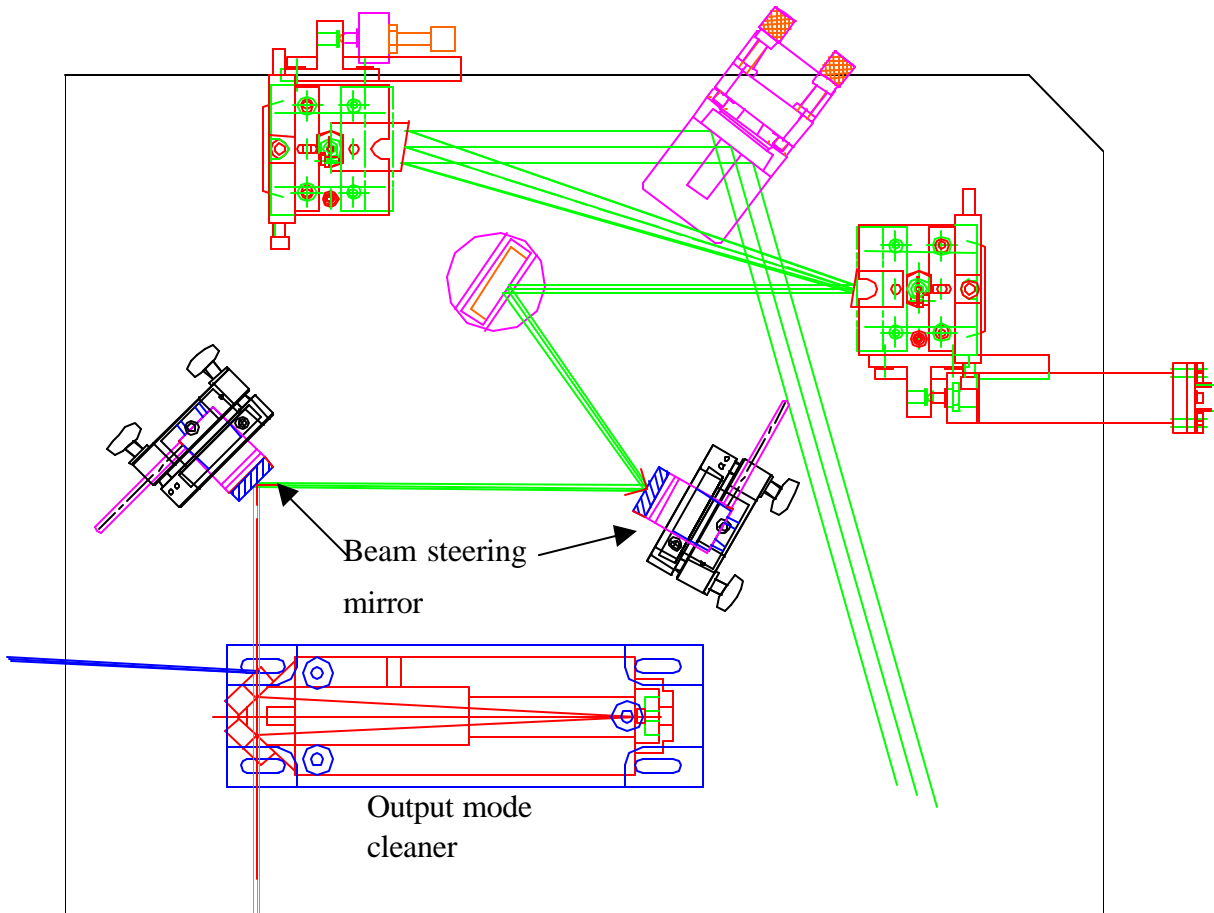


Figure 29: OMC beam steering

3.2.9.3.2 IFO Beam Steering Characteristics

3.2.9.3.2.1 IFO Beam Steering Performance Characteristics

Table 46: IFO beam steering performance characteristics

Parameter	Requirement	Actual
Spot size of OMC beam	0.37 mm	
Displacement steering	+/-0.37 mm	+/- 0.8 mm
Divergence angle of OMC beam	0.00092 rad	
Angular steering	0.00092 rad	+/- 0.004 rad
Resonant frequency		3500 Hz
Angle sensing		Internal strain gage

3.2.9.3.2.2 IFO Beam Steering Physical Characteristics

Table 47: IFO beam steering physical characteristics

Parameter	Requirement	Actual
Stiffness		0.0005 N/micrometer
Voltage cable		LEMOSA, 4 wire
Sensor cable		LEMOSA, 8 wire
Weight		60 g
Dimensions:		
diameter		25 mm
Length		29.5 mm

3.2.9.3.2.3 OMC Beam Steering Interface Definitions

3.2.9.3.2.3.1 Interfaces to other LIGO detector subsystems

3.2.9.3.2.3.1.1 Mechanical Interfaces

The PZT tilt mirrors will be mounted to the optics table inside the output chamber.

3.2.9.3.2.3.1.2 Electrical Interfaces

X and y tilt drive voltages and strain gage sensor signals for the PZT tilt mirrors will be supplied through a vacuum feedthrough connector external to the vacuum chamber.

3.2.9.3.2.3.1.3 *Optical Interfaces*

The steering mirrors will be placed on the centerline of the OMC beam and will not vignette the beam closer than the 100 ppm beam diameter.

3.2.9.3.2.4 *OMC Beam Steering Reliability*

Mean Time Between Failures (MTBF) of the OMC beam steering is the lifetime of the PZT tilt platform, which is expected to be the life of the IFO.

3.2.9.3.2.5 *OMC Beam Steering Interchangeability*

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.9.3.3 **OMC Beam Steering Isolator Precedence**

This section should list the relative importance of requirements (or goals) to be achieved by the design. TBD

3.2.9.3.4 **OMC Beam Steering Qualification**

Test and acceptance criteria. TBD

3.2.9.4 **Output Mode Cleaner**

3.2.9.4.1 **Introduction**

3.2.9.4.2 **Output Mode Cleaner Characteristics**

3.2.9.4.2.1 *Output Mode Cleaner Performance Characteristics*

TBD

3.2.9.4.2.2 *Output Mode Cleaner Physical Characteristics*

TBD

3.2.9.4.2.3 *Output Mode Cleaner Interface Definitions*

TBD

3.2.9.4.2.3.1 Interfaces to other LIGO detector subsystems

3.2.9.4.2.3.1.1 *Mechanical Interfaces*

3.2.9.4.2.3.1.2 *Electrical Interfaces*

3.2.9.4.2.3.1.3 *Optical Interfaces*

3.2.9.4.2.3.1.4 *Stay Clear Zones*

3.2.9.4.2.3.2 Interfaces external to LIGO detector subsystems

3.2.9.4.2.3.2.1 *Mechanical Interfaces*

3.2.9.4.2.3.2.2 *Electrical Interfaces*

3.2.9.4.2.3.2.3 *Stay Clear Zones*

3.2.9.4.2.4 *Output Mode Cleaner Reliability*

TBD

3.2.9.4.2.5 *Output Mode Cleaner Maintainability*

TBD

3.2.9.4.2.6 *Output Mode Cleaner Interchangeability*

TBD

3.2.9.4.3 Output Mode Cleaner Precedence

TBD

3.2.9.4.4 Output Mode Cleaner Qualification

Test and acceptance criteria.

3.2.9.5 AP2 ISC Optical Train

3.2.9.5.1 Introduction

The AP2 ISC optical train consists of the following elements: a fast-acting EO beam shutter to protect the sensors from excessive light levels, a photodiode to monitor the power transmitted through the output mode cleaner, a DC photodiode for detecting the gravity wave signal, and a video camera to monitor the beam mode shape.

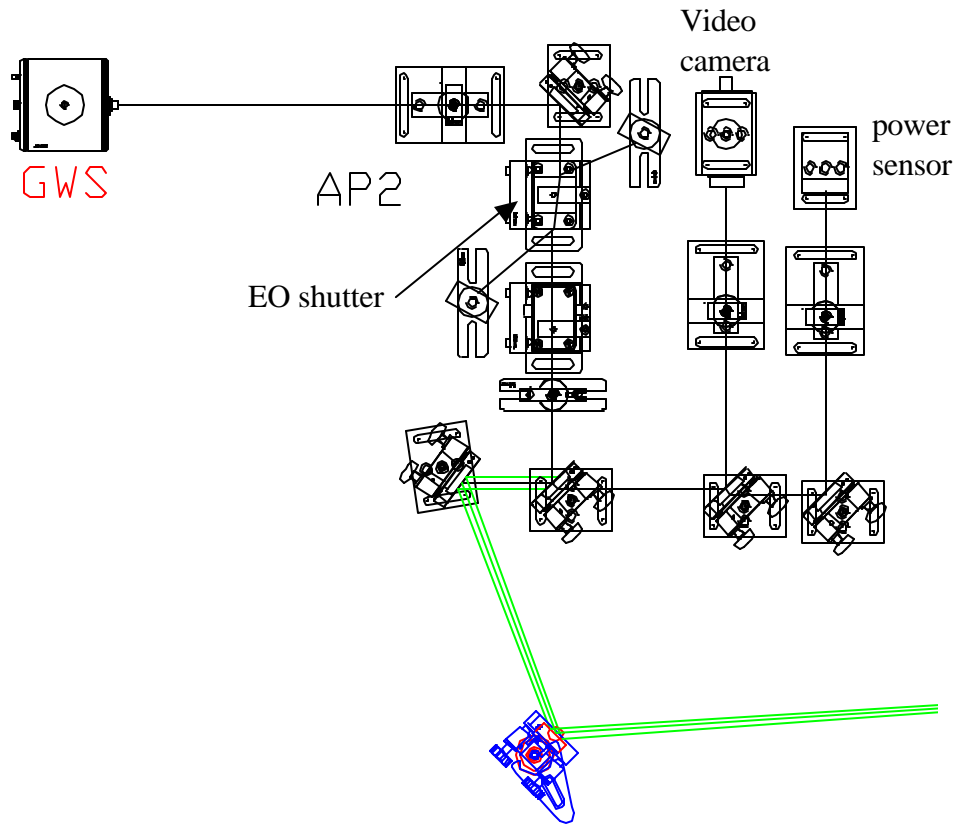


Figure 30: AP2 ISC Optical Train

3.2.9.5.2 AP2 ISC Optical Train Characteristics

3.2.9.5.2.1 AP2 ISC Optical Train Performance Characteristics

The AP2 beam sensing system shall detect the phase modulation on the antisymmetric IFO beam within the gravity wave band.

Table 48: AP2 ISC Optical Train Performance Characteristics

Parameter	Requirement	Actual
AP2 power ratio	0.005	0.005
GWS photodetector frequency response	DC - 10 KHz	DC - 10 KHz
Seismic velocity of GWS photodetector	TBD	TBD

3.2.9.5.3 AP2 ISC Optical Train Physical Characteristics

3.2.9.5.3.1 AP2 ISC Optical Train Physical Characteristics

Table 49: AP2 ISC Optical Train Physical Characteristics

Parameter	Requirement	Actual
Beam diameter, 100ppm	14 mm	14 mm

3.2.9.5.3.2 AP2 ISC Optical Train Interface Definitions

3.2.9.5.3.2.1 Interfaces to other LIGO detector subsystems

3.2.9.5.3.2.1.1 Mechanical Interfaces

The AP2 beam sensing system will be mounted at a beam height of 4 in to an external optical table adjacent to the output chamber.

3.2.9.5.3.2.1.2 Electrical Interfaces

The EO shutter, video camera, power detector, and GWS photodetector have electrical interfaces to CDS.

3.2.9.5.3.2.1.3 Optical Interfaces

The AP2 beam first steering mirror will be centered on the AP2 output beam.

3.2.9.5.3.2.1.4 Stay Clear Zones

The AP2 system will stay clear of the IMC_T, IMC_R, AP1, and SPS output beams.

3.2.9.5.3.3 AP2 ISC Optical Train Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the video camera, which should be equal to the life of the IFO.

3.2.9.5.3.4 AP2 ISC Optical Train Interchangeability

Specify the level at which components shall be interchangeable or replaceable. TBD

3.2.9.5.4 AP2 ISC Optical Train Precedence

TBD

3.2.9.5.5 AP2 ISC Optical Train Qualification

Test and acceptance criteria. TBD

3.3 Viewport

Optical quality viewports shall allow passage of the IFO input beam, the output sensing beams, and the optical lever beams, in and out of the vacuum enclosure, with minimum wavefront distortion and maximum transmissivity. Camera quality viewports shall provide a vacuum window through which video cameras can view the HR surface of the COC mirrors.

The type of viewport and the location are shown in Table 50: Viewports, types and locations.

Table 50: Viewports, types and locations

Location	Type
Ouput-chamber, 1	Optical quality, type 1
Ouput-chamber, 2	Optical quality, type 1
Ouput-chamber, 3	Optical quality, type 1
Input chamber, “T”	Camera
Input chamber, top	Camera
Mode cleaner chamber	Camera
BS chamber	Optical quality, type 2
East vertex chamber, mid	Optical quality, type 2
East vertex chamber, upper	Camera
South vertex chamber, mid	Optical quality, type 2
South vertex chamber, upper	Camera
East end chamber, mid	Optical quality, type 2
East end chamber, upper	Camera
South end chamber, mid	Optical quality, type 2
South end chamber, upper	Camera

3.3.1 Optical Quality Viewport

3.3.1.1 Introduction

Optical quality viewports with low reflectivity at 1064 nm (reflectivity type 1) shall be used to minimize the wavefront distortion and to maximize the transmissivity of the following main IFO beams and output sensing beams: main IFO input beam, OMC_R, IMC_T, IMC_R, AP1, SPS. Optical lever beams shall be transmitted through the optical quality viewports. The BS, ITM_x, ITM_y PO beams and the ETM transmission beams share a viewport with optical lever beams and will require a broadband AR coating of reflectivity type 2. The ETM transmission beam viewport shall be tilted in the vertical plane to minimize scattering into the IFO.

The flange that holds the tilted viewport is shown in Figure 31: Tilted viewport.

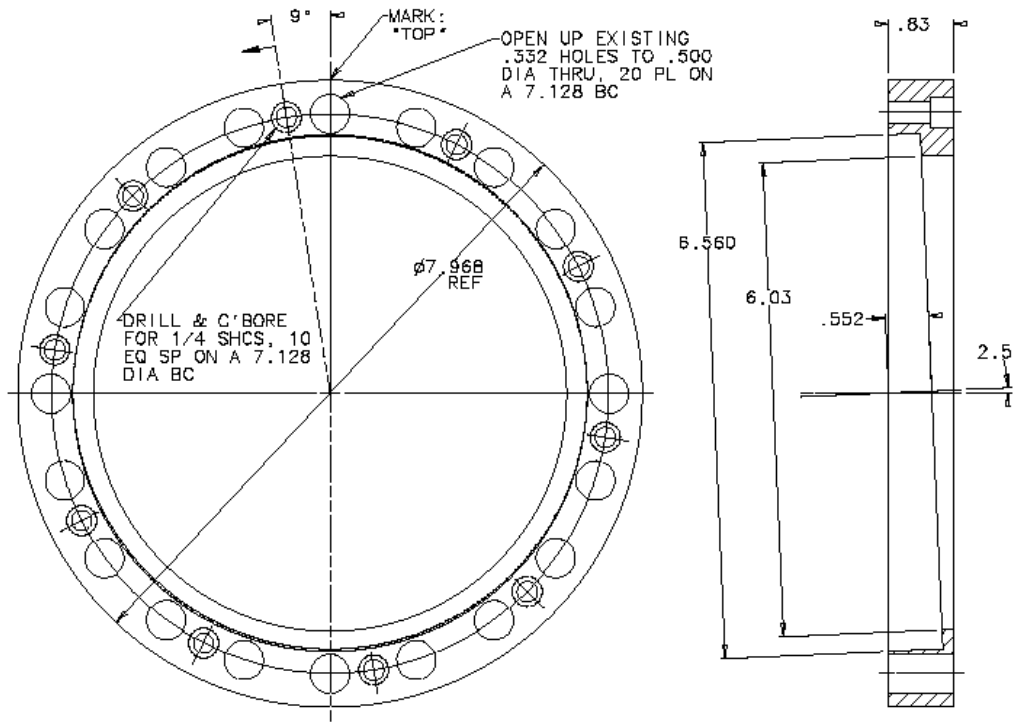


Figure 31: Tilted viewport

3.3.1.2 Optical Quality Viewport Characteristics

3.3.1.2.1 Optical Quality Viewport Performance Characteristics

Table 51: Optical quality viewport performance characteristics

Parameter	Requirement	Actual
Tilt angle	2.5 deg	2.5 deg
Scattering BRDF, sr^{-1}	< 0.04	TBD
Reflectivity 1 @ 1064 nm, normal incidence		< 0.1 %
Reflectivity 2 @ 630 - 1064 nm, normal incidence		< 0.75 %

3.3.1.2.2 Optical Quality Viewport Physical Characteristics

Table 52: Optical quality viewport physical characteristics

Parameter	Requirement	Actual
Diameter		6.500 +/- 0.010 in
Thickness		1.000 +/- 0.010 in
Material		BK7
Wedge angle		0.5 deg
Flatness (on central 5.75 dia.)		<1/4 wave @ 633 nm
Surface quality		10-5 scratch & dig

3.3.1.2.3 Optical Quality Viewport Interface Definitions

3.3.1.2.3.1 Interfaces to other LIGO detector subsystems

3.3.1.2.3.1.1 Mechanical Interfaces

The viewport is sealed with an o-ring inside a vacuum flange, which is sealed to the port on the side of the vacuum chambers.

3.3.1.2.3.1.2 Optical Interfaces

All output sensing beams, the main IFO beam, and optical lever beams will pass through the viewports.

3.3.1.2.3.1.3 Stay Clear Zones

3.3.1.2.4 Optical Quality Viewport Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the IFO.

3.3.1.2.5 Viewports Interchangeability

All tilted viewports are interchangeable.

3.3.1.3 Optical Quality Viewport Qualification

Test and acceptance criteria.

3.3.2 Camera Viewport

3.3.2.1 Introduction

Camera viewports shall be located in every chamber that contains COC mirrors, to allow viewing of the HR surface of the mirror with a visible and IR camera.

The camera viewports are constructed of 7056 glass sealed to a Kovar sleeve in a standard conflat flange.

3.3.2.2 Camera Viewport Characteristics

3.3.2.2.1 Camera Viewport Performance Characteristics

Table 53: Camera viewport performance characteristics

Parameter	Requirement	Actual
Absorptivity @ 630 - 1064 nm		< 20 %
Reflectivity @ 1064 nm, over central 5.0 dia, normal incidence		< 0.1 %

3.3.2.2.2 Camera Viewport Physical Characteristics

Table 54: Camera viewport physical characteristics

Parameter	Requirement	Actual
Conflat dia.		8.0 in
View diameter		5.38 in
Thickness		0.375 in
Material		7056
Wedge angle		0.5 deg

3.3.2.2.3 Camera Viewport Interface Definitions

3.3.2.2.3.1 Interfaces to other LIGO detector subsystems

3.3.2.2.3.1.1 Mechanical Interfaces

The viewport is sealed in a vacuum flange with a glass-to-metal seal, which is sealed to the port on the side of the vacuum chambers.

3.3.2.2.3.1.2 Optical Interfaces

Visible and IR video cameras will view inside the vacuum chambers through the viewports.

3.3.2.2.3.1.3 Stay Clear Zones

3.3.2.2.4 Camera Viewport Reliability

Mean Time Between Failures (MTBF) is expected to be the life of the IFO.

3.3.2.3 Camera Viewport Qualification

Test and acceptance criteria. TBD

4 General Requirements

4.1 Environmental Conditions

The Optical Systems and Sensing subsystems will operate in a temperature and humidity controlled laboratory environment. Prior to assembly, the components of the Optical Systems and Sensing subsystems will be subjected to normal commercial shipping and handling environments.

4.2 Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable for forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

4.3 Design and Construction

The design and construction of standard purchased parts shall be in accordance with good commercial practices.

The design and construction of the Optical Systems and Sensing subsystem shall allow adequate cleaning, either on site or at an appropriate outside vendor, and shall fit inside the available vacuum baking ovens.

4.3.1 Materials and Processes

The materials and processes shall be compatible with the LIGO approved materials list.

4.3.1.1 Finishes

External surfaces requiring protection shall be painted or otherwise protected in a manner to be approved.

- Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes.
- All materials shall have non-shedding surfaces.
- Aluminum components used in the vacuum shall not have anodized surfaces.

4.3.1.2 Materials

A list of currently approved materials for use inside the LIGO vacuum envelope can be found in LIGO Vacuum Compatible Materials List (LIGO-E960022). All fabricated metal components exposed to vacuum shall be made from stainless steel, copper, or aluminum. Other metals are subject to LIGO approval. Pre-baked viton (or fluorel) may be used subject to LIGO approval. All materials used inside the vacuum chamber must comply with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D).

Only dry-plated lubricating films of vacuum compatible materials such as silver and gold are permitted within the vacuum chamber.

The lenses shall be fabricated from optical grade fused silica substrate with durable AR coatings.

4.3.1.3 Processes

4.3.1.3.1 Welding

4.3.1.3.2 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D). To facilitate final cleaning procedures, parts should be cleaned after any processes that result in visible contamination from dust, sand or hydrocarbon films.

Materials shall be joined in such a way as to facilitate cleaning and vacuum preparation procedures; i.e. internal volumes shall be provided with adequate openings to allow for wetting, agitation and draining of cleaning fluids and for subsequent drying.

Lenses shall be cleaned using standard laboratory optical cleaning procedures.

4.3.1.4 Component Naming

All components shall be identified using the LIGO Naming Convention (LIGO-E950111-A-E). This shall include identification (part or drawing number, revision number, serial number) physically stamped on all components, in all drawings and in all related documentation.

4.3.2 Workmanship

Custom manufactured parts shall be free from defects with a general high quality appearance of the finished product. Workmanship of standard purchased parts shall be in accordance with good commercial practices.

Lenses shall be made in conformance with laser quality commercial practices.

4.3.3 Safety

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.

4.3.4 Human Engineering

NA

4.4 Assembly and Maintenance

Assembly fixtures and installation/replacement procedures shall be developed in conjunction with the hardware design. These shall include (but not be limited to) fixtures and procedures for:

- Bench-alignment of optical assemblies

- In site alignment of optical assemblies
- Assembly of the in-vacuum components in a clean room (class 100) environment
- Installation and assembly of components into the vacuum chambers

4.4.1.1.1 Maintainability

Optical elements on external optical benches will require accessibility to they can be cleaned periodically. The MTTR depends upon the cleanliness of the environment.

4.4.1.1.2 Interchangeability

Common elements, with ordinary dimensional tolerances, will be interchangeable. Like commercial optical elements on external optical benches are interchangeable in the optical mounts. However, due to the tolerance on focal lengths, a readjustment of the lens spacing may be necessary to achieve optimum performance.

4.5 Documentation

The documentation shall consist of working drawings, assembly drawings, and alignment procedures.

4.5.1 Specifications

Specifications for the purchase of specialized components and assemblies such as Faraday isolator, optical mirrors, windows, and lenses shall be developed.

4.5.2 Design Documents

The following documents will be produced:

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

4.5.3 Engineering Drawings and Associated Lists

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

4.5.4 Technical Manuals and Procedures

4.5.4.1 Procedures

Procedures shall be provided for the following:

- Initial installation and setup of equipment

- Normal operation of equipment
- Normal and/or preventative maintenance
- Installation of new equipment
- Troubleshooting guide for any anticipated potential malfunctions

4.5.4.2 Manuals

Available equipment manuals shall be provided as appropriate.

4.5.5 Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

4.5.6 Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

4.6 Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

5 Quality Assurance Provisions

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3. TBD

5.1 General

This should outline the general test and inspection philosophy, including all phases of development. TBD

5.1.1 Responsibility for Tests

Who is responsible for testing? TBD

5.1.2 Special Tests

5.1.2.1 Engineering Tests

List any special engineering tests that are required to be performed. Engineering tests are those, which are used primarily for the purpose of acquiring data to support the design and development. TBD

5.1.3 Configuration Management

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

5.2 Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix, Appendix 1 (See example in Appendix). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

5.2.1 Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

5.2.2 Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

5.2.3 Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

5.2.4 Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

5.2.5 Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture's specifications and shall have a calibration sticker showing the current calibration status.

6 Preparation for Delivery

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

6.1 Preparation

- Vacuum preparation procedures as outlined in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D) shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts.

6.2 Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items should use for guidance military specification MIL-C-104B, Crates, Wood, Lumber, and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges should accompany the crates during all transits.

For all components that are intended for exposure in the vacuum system, the shipping preparation shall include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). Purge the bag with dry nitrogen before sealing.

6.3 Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified. The identification shall enable the complete history of each component to be maintained (in association with Documentation "travelers"). A record for each component shall indicate all weld repairs and fabrication abnormalities.

For components and parts that are exposed to the vacuum environment, marking the finished materials with marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces that are not hidden from view. Engraving and stamping are also permitted.