LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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The Input Optics
As-Built Description

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1 INTRODUCTION

1.1. Purpose

This document along with supporting analysis documents presents the final design for the LIGO Input Optics. The design information in this document supersede that presented in the IOO Preliminary and Conceptual Designs and is intended to present a detailed final design for the LIGO Input Optics Subsystem which conform to the *Input Optics Design Requirements*, LIGO-T960093-00-D. This document is intended for the LIGO Detector Team.

1.2. Scope

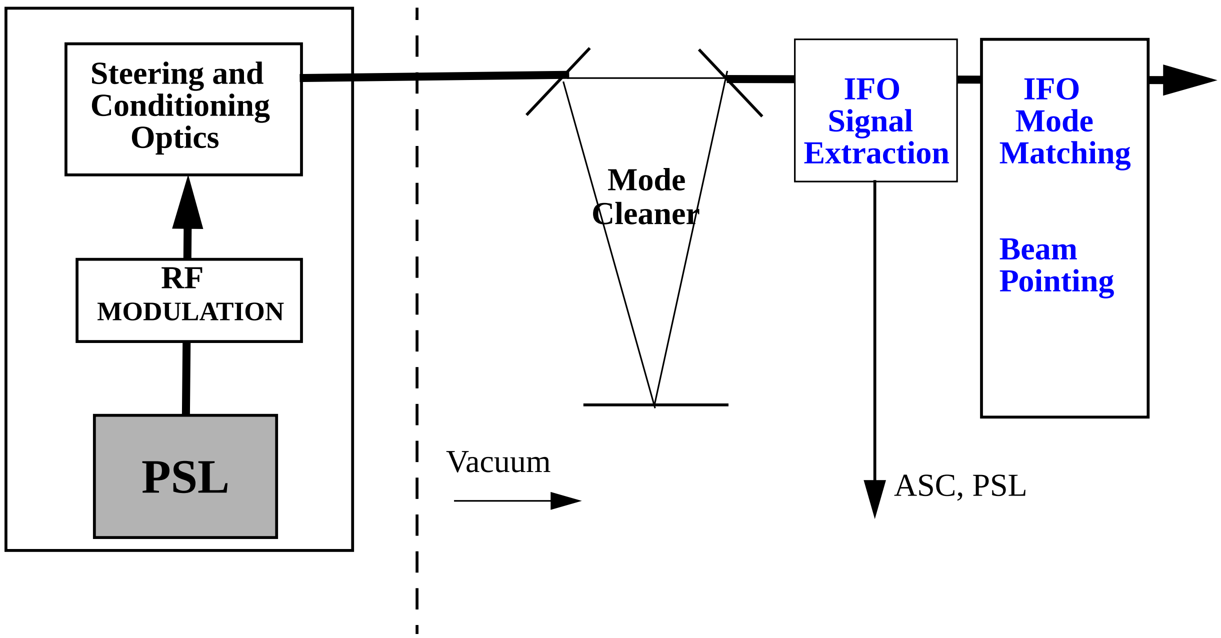
The IOO provides for the conditioning of the laser light after the PSL and before the IFO input, and for the disposition of the IFO reflected light to the LSC and ASC subsystems. It includes RF phase modulation of the light for the generation of resonant and non-resonant sidebands; mode-matching, lock acquisition and operation of the mode cleaner; mode matching of the light to the IFO; beam steering into the IFO; and diagnostic beam pick-offs for the LSC/ASC subsystems.

1.2.1. IOO Subsystems

The Input / Output (IOO) subsystem layout consists of the following units, schematically shown in Figure 1:

- RF modulation
- Steering and conditioning optics
- Mode cleaner and controls
- IFO mode matching and beam pointing
- IFO signal extraction for ASC
- Signal extraction for PSL intensity control

Figure 1: IOO Subsystem Components



1.3. Document Organization

1.3.1. Definitions

- TEM_{00} Gaussian beam: A beam of electromagnetic radiation, in which the transverse electric field varies as $E = E_0 e^{-r^2/w^2}$, where w is the beam spot size and E_0 is the electric field strength at r=0.
- Spot size: The characteristic size for Gaussian laser beams, defined as the distance (radius) at which the electric field drops to $1/e$ times the maximum value, E_0 (at $r = 0$).
- Beam Divergence Half Angle - The far field angular divergence θ_d of a Gaussian beam is defined in terms of the half angle formula $\theta_d/2 = \dfrac{\lambda}{\pi w_0}$
- Modulation index Γ: The application of RF sidebands using an EOM results in a output field $E_{mod} = E_{in} e^{-i\omega t - i\Gamma \cos \Omega t}$ where ω and Ω are the carrier and modulation frequencies and E_{in} is the input field amplitude.

1.3.2. Acronyms

ASC	Alignment Sensing / Control (detector subsystem)
BS	Beamsplitter (optical component)
CDS	Control and Data System (detector subsystem)
CIT	California Institute of Technology
COC	Core Optics Components (detector subsystem)
COS	Core Optics Support (detector subsystem)
DC	Direct Current (steady state - low frequency)
EOM	Electro-Optic Modulator (optical hardware)
ETM	End Test Mass (optical component)
FI	Faraday Isolator (optical component)
FR	Faraday Rotator (optical component)
HAM	Horizontal Access Module
IFO	LIGO Interferometer
IOO	Input Optics (detector subsystem, formerly named Input / Output Optics)
ITM	Input Test Mass (optical component)
LHAM	Horizontal Access Module at Louisiana Site
LIGO	Laser Interferometer Gravitational-Wave Observatory
LSC	Length Sensing / Control (detector subsystem)
LOS	Large Optic Suspension
LVEA	Laser and Vacuum Equipment Area (of the LIGO observatories)
MC	Mode Cleaner
MIT	Massachusetts Institute of Technology
MMT	IFO Mode Matching Telescope
Nd:YAG	Neodynium doped Yttrium Aluminum Garnet (laser gain medium)
PDD	Preliminary Design Document
PDH	Pound-Drever-Hall
PMC	Pre-Mode Cleaner (Component in PSL Subsystem)
PSL	Pre-Stabilized Laser (detector subsystem)
PZT	Piezo-electric Transducer (mechanical hardware)
RC	Radius of Curvature of a Reflective Mirror
RF	Radio Frequency
RM	Recycling Mirror
SEI	Seismic Isolation
SOS	Small Optic Suspension
UF	University of Florida
WFS	Wave Front Sensors
WHAM	Horizontal Access Module at Washington Site

1.3.3. Relevant Documents

1.3.3.1 LIGO Documents

Input Optics Design Requirements Document, J. Camp, D. Reitze, and D. Tanner, *LIGO-T960093-00-D*
Input Optics Conceptual Design, J. Camp, D. Reitze, and D. Tanner, *LIGO-T960170-00-D*

Input Optics Preliminary Design, Rana Adhikari, Tom Delker, David Reitze, Qi-Ze Shu, David Tanner, Sanichiro Yoshida, *LIGO-T9701xx-00-D*
2k IOO Global Coordinates, A. Bengston, David Tanner, *LIGO-E010035-00-Z*
4k LHO IOO Global Coordinates, A. Bengston, David Tanner, *LIGO-E010025-01-Z*
4k LLO IOO Global Coordinates, A. Bengston, David Tanner, *LIGO-E010034-00-Z*
Mode Cleaner Length/Frequency Control Design, P. Fritschel, N. Mavalvala, D. Ouimette, LIGO-T970218-01-D
Absorption in the Core Optics and LIGO Sensitivity, J. Camp and B. Kells, LIGO-T970097-01-D
Alignment Sensing/Control Design Requirement Document, P. Fritschel, *LIGO-T952007-03-I*
Alignment Sensing/Control Preliminary Design, P. Fritschel, G. Gonzalez, D. Sigg, M. Zucker, *LIGO-T970060-00-D*
Detector Subsystems Requirements, D. Shoemaker, *LIGO-E960112-05-D*
Design Considerations for LIGO Mode-Matching Telescopes, T. Delker, R. Adhikari, S Yoshida, and D. Reitze, *LIGO-T970143-00-D*
Effects of Stray Magnetic Fields Generated by Faraday Isolators on Suspended Optical Components, S. Yoshida, R. Adhikari, and D. Reitze, *LIGO-T970149-00-D*
Frequency Stabilization: Servo Configuration & Subsystem Interface Specification, P. Fritschel, *LIGO-T970088-00-D*
Impact of Non-resonant Sidebands on Length Sensing Signals, J. Camp, *LIGO-T970097-00-D*
Initial length precision of LIGO suspended cavities, J. Camp, *LIGO-T960181*.
LIGO cavity lengths and modulation frequencies, D.B. Tanner, *LIGO-T-970156-03-D*
LHO Mode Cleaner Commissioning Status - Directors Review, Peter Fritschel, LIGO-G000006-00-D
MIT Meeting on RF Modulation, David Shoemaker, LIGO-T970155-00-D
Modal Model Update 4: Mode-Matching, D. Sigg, *LIGO-T960116-00-D*
Modal Model Update 6: Mode Cleaner, D. Sigg, *LIGO-T960118-00-D*
Mode Cleaner Noise Sources, J. Camp, *LIGO-T960165-00-D*
Mode Matching Wavefront Sensor, Qi-Ze Shu, Rana Adhikari, David Reitze, David Tanner, *LIGO-T980021-00-D*
Proposed initial detector MC and RC baseline lengths, M. Zucker and P. Fritschel, *LIGO-T960122-00-I.*
Recycling cavity and mode cleaner baseline dimensions, D. Coyne, *LIGO-T970068-00-D*
Small Optics Suspensions Final Design, S. Kawamura, *LIGO-T970135-02-D*
LIGO Cavity Lengths and Core Optic Positions, D. Coyne, *LIGO-E000053-02-D*
LIGO Faraday Isolator Measurements Nergis Mavalvala, *LIGO-T030132-00-W*

1.3.3.2 Non-LIGO Documents

Heating by Optical Absorption and the Performance of Gravitational Wave Detectors, W.Winkler, K. Danzmann, A. Ruediger, and R. Schilling, Phys Rev A, 44, 7022.
Optical mode cleaner with suspended mirrors, A. Araya, N. Mio, K. Tsubono, K. Suehiro, S. Telada, M. Ohashi, and M. Fujimoto, Appl. Opt. **39**, 1446 (1977).
The response of a Fabry-Perot optical cavity to phase modulation sidebands for use in electro-optic control systems, K.D. Skelton, and K.A. Strain, Applied Optics Lasers, *in press.* **[UPDATE]**
Alignment of Resonant Optical Cavities, D. Anderson, Appl. Opt. ***23****, 2944 (1984)*
Determination and Optimisation of Mode matching into Optical Cavities Using Heterdyne

Detection, Guido Mueller, Qi-ze Shu, Rana Adhikari, D.B.Tanner, David Reitze, Daniel Sigg, Nergis Mavalvala, and Jordan Camp, Optics Lett.**25**, 266-268 (2000).

Additional information can be found in the LIGO elogs found at

www.ligo.caltech.edu

and at the LHO Image Map found at

www.ligo-wa.caltech.edu/~cgray/interferometers.html

2 OVERVIEW OF THE FINAL DESIGN

2.1. Detailed Components Specification

Table 1: The complete list of IOO components

	DCC Drawing Number
Half Round MC Tube Baffle	D030374
RM Offset Beam Dump	D010087
MC Baffle	D980689
MC1 Errant Beam Baffle	D030410, D030401, D030358
MC2 Errant Beam Baffle	D030406, D030398, D030356
MC3 Errant Beam Baffle	D030409, D030400, D030357
MMT1 Errant Beam Baffle	D030390, D030388, D030354
MMT2 Errant Beam Baffle	D030407, D030399, D030377
MMT3 Errant Beam Baffle	D030408, D030405, D030359
Faraday Isolator	
DLC Steering Mirrors	DLC-500-1072HV
In-Vac. Non-Suspended Steering Mirrors	D980191
MC1	E980141
MC2	E980140 4k E980139 2k
MC3	E980141
MMT1	E980138 4k E980136 2k
MMT2	E980137 4k E980135 2k
MMT3	E980134

Table 1: The complete list of IOO components

	DCC Drawing Number
SM1	
MMT2 Riser	D980504 4k D980503 2k
MC2 Riser	
IOO/PSL Periscope	D010231
SOS Assembly	D960001

3 SUBSYSTEM INTERFACES

By and large, optical, mechanical, and electrical interfaces have remained the same as those presented in the IOO PDD. The following constitutes a complete list of interfaces between the IOO and other LIGO subsystems.

3.1. PSL/IO Interfaces

The PSL delivers the main LIGO laser beam to the IOO and receives a diagnostic beam for intensity stabilization after the IOO MC.

3.1.1. Main Beam

The optical interfaces between the PSL and IOO are given in Table 2 and Table 3. The IO/PSL interface was chosen to be located at the position of the waist in the PMC. The PSL system will need to add components downstream of this, however they will not appreciably change the beam propogation characteristics.

Table 2: IOO/PSL Optical Interfaces for the 2km IFO

Optical Interface	*Interface Description*	*Value/Tolerance*	*Coordinates*
Main Beam	Location of Handoff of Main Beam from PSL to IOO subsystems	$(85\ in \pm 0.10 in,$ $23\ in \pm 0.10 in,$ $3.0\ in \pm 0.1 in)$	PSLWA2K local coordinate system (2 km PSL/IOO table)
	Waist Size	0.371 mm $\pm 0.1 mm$	
	Waist Position Uncertainty	$\pm 5 cm$	Measured from PSL/IOO Interface Location
	Polarization	P pol.	
	Polarization Ratio	>100:1	
	Beam Power in TEM_{00}	8.5 W	
	Beam Power in Higher Order Modes	<< 1 W	
PSL Intensity Stabilization Pickoff	Location of Handoff of Diagnostic Intensity Stabilization Beam from the IOO to the PSL	PSL Intensity Stabilization Photodiode	IOT7 local coordinate system (2 km IOO ISC table)

Optical Interface	*Interface Description*	*Value/Tolerance*	*Coordinates*
	Beam Size at Interface	$2mm \pm 0.2mm$	
	Beam Divergence Half Angle	0.3 mrad (converging)	
	Beam Power at Interface	25 mW	

Table 3: IOO/PSL Optical Interfaces for the 4 km IFO

Optical Interface	*Interface Description*	*Value/Tolerance*	*Coordinates*
Main Beam	Location of Handoff of Main Beam from PSL to IOO subsystems	(85 $in \pm 0.10 in$, 23 $in \pm 0.10 in$, 3.0 $in \pm 0.1 in$)	4 km PSL/IOO table local coordinate system
	Waist Size	0.371mm	
	Waist Position	$\pm 0.5 cm$	Measured from Interface Location
	Polarization	P pol.	
	Polarization Ratio	>100:1	
	Beam Power in TEM_{00}	8.5 W	
	Beam Power in Higher Order Modes	<< 1 W	
PSL Intensity Stabilization Pickoff	Location of Handoff of Diagnostic Intensity Stabilization Beam from the IOO to the PSL	PSL Intensity Stabilization Photodiode	IOT1 local coordinate system (2 km IOO ISC table)
	Beam Size at Interface	$2mm \pm 0.2mm$	
	Beam Divergence Half Angle	0.3 mrad (converging)	
	Beam Power at Interface	25 mW	

3.2. COC/IO Interfaces

The IOO delivers the main beam to the COC at the recycling mirror.

3.2.1. Optical Interfaces

Table 4 and Table 5 display the IOO/COC optical interfaces for the 2 km and 4 km IFO.

Table 4: IOO/COC Optical Interfaces for the 2 km IFO

Optical Interface	*Interface Description*	*Value/Tolerance*	*Coordinates*
Main Beam	Location of Handoff of laser beam from IOO to COC sub-systems	(12.2786 m±0.5mm, 9.0597 m±0.5mm, 0.045 m±0.5mm)	Global LIGO Coordinate System
	Propagation Direction	(-1.000000, -0.00013700, 0.00000000)	Direction Cosines
	Beam Size (1/e field radius)	3.22 cm	
	Beam Divergence Half Angle	11.5 μrad	
	Polarization	P pol.	
	Polarization Ratio	>100:1	
	Beam Power in TEM_{00}	> 6 W	
	Beam Power in Higher Order Modes	< 4 x 10^{-5} W	

Table 5: IOO/COC Optical Interfaces for the 4 km IFO

Optical Interface	*Interface Description*	*Value/Tolerance*	*Coordinates*
Main Beam	Location of Handoff of laser beam from IOO to COC sub-systems	(-4.6906 m±0.5mm, 0.212 m±0.5mm, 0.0278 m±0.5mm)	Global LIGO Coordinates
	Propagation Direction	(1.000000, 0.0013673, 0.0000000)	Direction Cosines
	Beam Size (1/e field radius)	3.64 cm	
	Beam Divergence Half Angle	10.7 μrad	
	Polarization	P pol.	

Optical Interface	*Interface Description*	*Value/Tolerance*	*Coordinates*
	Polarization Ratio	>100:1	
	Beam Power in TEM_{00}	> 6 W	
	Beam Power in Higher Order Modes	< 4 x 10^{-5} W	

3.3. ISC/IO Interfaces

3.3.1. Diagnostic Sensing Beams

The IOO delivers diagnostic beams to the ISC subsystems from Faraday Isolators located in WHAM 1 (WA 4 km IFO), in WHAM 7 (WA 2 km IFO), and LHAM 11 (LA 4 km IFO) through HAM viewports. These beams will have spot sizes of 2 mm ± 0.1 mm with nominal powers of 300 mW and up to 6 W during lock acquisition of the IFO.

Table 6: IOO/ISC Optical Interfaces for the 2 km IFO

Optical Interface	*Interface Description*	*Value/Tolerance*
COC Length/ Alignment Sensing Beam	Location of Handoff of back-reflected diagnostic beam from COC through IOO to ISC subsystem	Viewport WH7A1F4
	Beam Size at Interface	1.82 mm $\pm 0.1 mm$
	Beam Divergence Half Angle	0.186 mrad (converging)
	Incident Angle on Viewport	5˚
	Beam Power	0.5 W
	Polarization	S pol.

Table 7: IOO/ISC Optical Interfaces for the 4 km IFO

Optical Interface	*Interface Description*	*Value/Tolerance*
COC Length/ Alignment Sensing Beam	Location of Handoff of back-reflected diagnostic beam from COC through IOO to ISC subsystem	Viewport WH1A1F4
	Beam Size at Interface	0.165 mm $\pm 0.1 mm$
	Beam Divergence Half Angle	0.208 mrad (diverging)
	Incident Angle on Viewport	5°
	Beam Power	0.5 W
	Polarization	S pol.

3.3.2. Optical Levers

The ISC provides optical levering for the mode matching telescope mirror MMT3 in the 2,4 km IFOs. The transmitter/receivers for the MMT3 optical lever are located on HAMs piers just outside viewports.

Provisions for temporary optical levers have been made for MC2, MC3, and MMT2 in all three LIGO IFOs.

3.4. SEI Mechanical

The in-vacuum IOO components are located on the seismic isolation stacks located in WHAM 1,2,7,8 and LHAM 1,2.

3.5. VACUUM

3.5.1. Mechanical

Viewports for bringing the main beam into the vacuum system and taking diagnostic beams out of the vacuum system to their respective diagnostic functions are located on the HAM doors. The locations are given in Table 8.

Table 8: Locations of IOO Viewports

Viewport	*Location*
2 km Main Beam Vacuum Feed-in	WH7B2F3
2 km PSL Intensity Stabilization Feed-out	WH7A2F5
2 km MC Reflected Beam Feed-out	WH7A2F4
4 km Main Beam Vacuum Feed-in	WH1B2F3, LH1B2F3
4 km PSL Intensity Stabilization Feed-out	WH1A2F5, LH1A2F5
4 km MC Reflected Beam Feed-out	WH1A2F4, LH1A2F4

A light pipe which encloses the main beam feed-in from the PSL/IOO table to the vacuum system is attached to the WHAM 1,7 and LHAM1 Viewports WH7B2F3, WH1B2F3, and LH1B2F3. A lockable shutter is provided on this light pipe.

3.6. CDS

3.6.1. Mechanical

Sensor/actuator heads for the Small Optics Suspensions were supplied by the CDS group. IOO mounted the Sensor/actuator heads in the SOS suspensions during assembly and balancing prior to the in-vacuum installation.

3.6.2. Electrical

The RF modulation signals for the resonant, non-resonant, and mode cleaner PDH sidebands are supplied to the IOO EOMs from CDS. The signal characteristics are given in Table 9.

Table 9: RF Signals into IOO

Sideband	*Frequency* (MHz)	*Modulation Depth* Γ	*Voltage, (pk-pk)*	*RF Power, RMS (into 50* Ω)
4 km IFO resonant, typ “ max	24.481	0.47 * 1	4.7 V 10 V	55 mW 0.25 W
4 km IFO non-resonant	61.204	0.055 **	0.6 V	~1 mW
4 km MC	33.289	0.1	1 V	2.5 mW
2 km IFO resonant, typ “ max	29.508	0.47 1	4.7 V 10 V	55 mW 0.25 W
2 km IFO non-resonant	68.851	0.055	0.6 V pk-pk	~1 mW
4 km MC	26.717	0.1	1 V	2.5 mW

Note: Modulation indices Γ are nominal; the modulation depths for the resonant sidebands are to range from 0-1. The range of modulation depth for the non-resonant sideband will be provided by ISC.

* Measured to be 0.295 at LHO. See LHO Detector elog Jan 30, 2004, Matone, Sigg.

** Measured to be 0.1 at LHO. See LHO Detector elog Jan 30, 2004, Matone, Sigg.

3.6.2.1 EMI Control

The maximum RF power in the Pockel’s cells in LIGO are less than 1/4 W and it will generate radiation field of about 0.5 V/m at a distance of 5 meters away from the source if that power is totally radiated (impedance matched to an antenna). The Pockel’s cell to be used has a metal box housing which has two openings of 2 mm in diameter while the wavelength of the RF modulation filed to be used is at least 5 meters. The radiation from the opening will be negligibly small. However, the cables for the RF power need to be grounded at both ends and run as close to the grounding surface as possible.

3.6.3. PSL Table Mirror Actuators

ISC provides mode-cleaner length and alignment control signals to the PI-E-503 3-channel amplifier module located in CDS IOO racks 1x4 (4k IFOs) and 2x6 (2k IFO). CDS in turn provides signals to the PI S-330.30 two-axis tilting mirror actuators on the IOO/PSL table and the periscope.

3.6.4. Small Optics Suspensions Controls

CDS takes input signals from the IOO for controlling small optics suspensions and delivers control signals to the suspensions. Table 10 displays the SOS interfaces to CDS.

Table 10: CDS SOS Interfaces

IFO	*Suspension*	*CDS Input from IOO*	*CDS Output to SOS*
2km, 4km	MC1	MC WFS Input Signal	Sensor/Actuator Control Signals
2km, 4km	MC2	MC RFPD	Sensor/Actuator Control Signals
2km, 4km	MC3	MC WFS Input Signal	Sensor/Actuator Control Signals
2km, 4km	SM1	DC Input Control Signal	Sensor/Actuator Control Signals
2 km	SM2	DC Input Control Signal	Sensor/Actuator Control Signals
2km, 4km	MMT1	DC Input Control Signal	Sensor/Actuator Control Signals
2km, 4km	MMT2	DC Input Control Signal	Sensor/Actuator Control Signals

3.6.5. Small Optics Mode Cleaner Suspensions

The mode cleaners employ Small Optic Suspensions. These are described in *Small Optics Suspensions Final Design*, S. Kawamura, *LIGO-T970135-02-D.* The electronics that drive the suspensions are designed to the following requirements:

Table 11: SOS Parameters for the Mode Cleaners

Parameter	*Value*
Length Dynamic Range	27 μm pk-pk
Angular Dynamic Range	1.5 mrad pk-pk
Noise	3 x 10^{-18} m/rtHz

3.6.6. Suspensions for the MMT (2k and 4k)

The mode-matching telescope employs Small Optic Suspensions for MMT1 and MMT2.(The Steering Mirrors are in identical SOS's.) The suspensions are described in Small Optics Suspensions Final Design, S. Kawamura, LIGO-T970135-02-D. MMT3 is placed in a Large Optic Suspension supplied by SUS. The electronics that drive the suspensions are designed to the requirements shown in Table 12.

Table 12: SOS/LOS Parameters for the MMT

Parameter	*Suspension*	*Value*
Length Dynamic Range	SOS	500 μm pk-pk
Angular Dynamic Range	SOS	>5 mrad pk-pk
Noise	SOS	5 x 10^{-16} m/rtHz
Length Dynamic Range	LOS	40 μm pk-pk
Angular Dynamic Range	LOS	1 mrad pk-pk
Noise	LOS	5 x 10^{-16} m/rtHz

4 IOO LAYOUT

4.1. PSL/IOO Table

The PSL table contains the following IOO components:

- Phase modulators for the application of RF sidebands
- Lenses for mode matching into the MC
- A periscope for the stepping the beam up to the HAM viewport.
- Beam tubes to minimize air current and acoustic perturbations

4.1.1. Mechanical

The mechanical layout for the PSL table showing complete optical and opto-mechanical mounting is shown in Figure 2 for the 4k IFO. (4k PSL: LIGO-D000336-00-W, T. Mahood, 1/4/2001, updated J. Garofoli/R. Savage 5/7/2004) During the spring of 2004, both the LHO 2k and 4k PSL components were relaid as per the updated schematic below in order to improve the modematching and throughput of power into the MC.

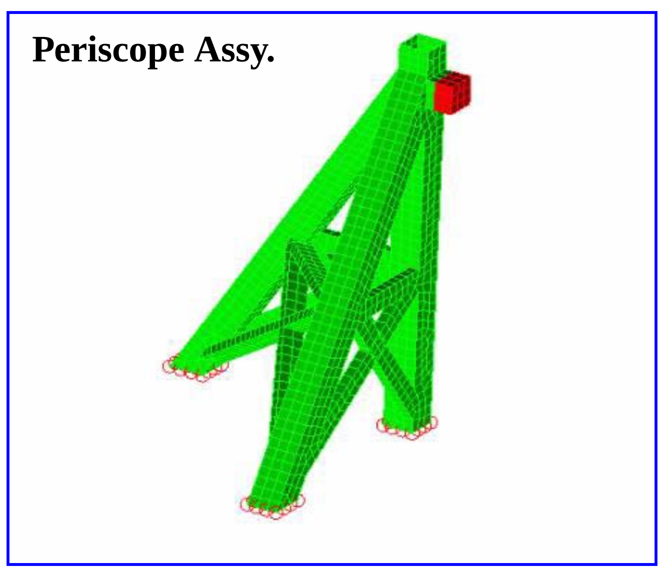
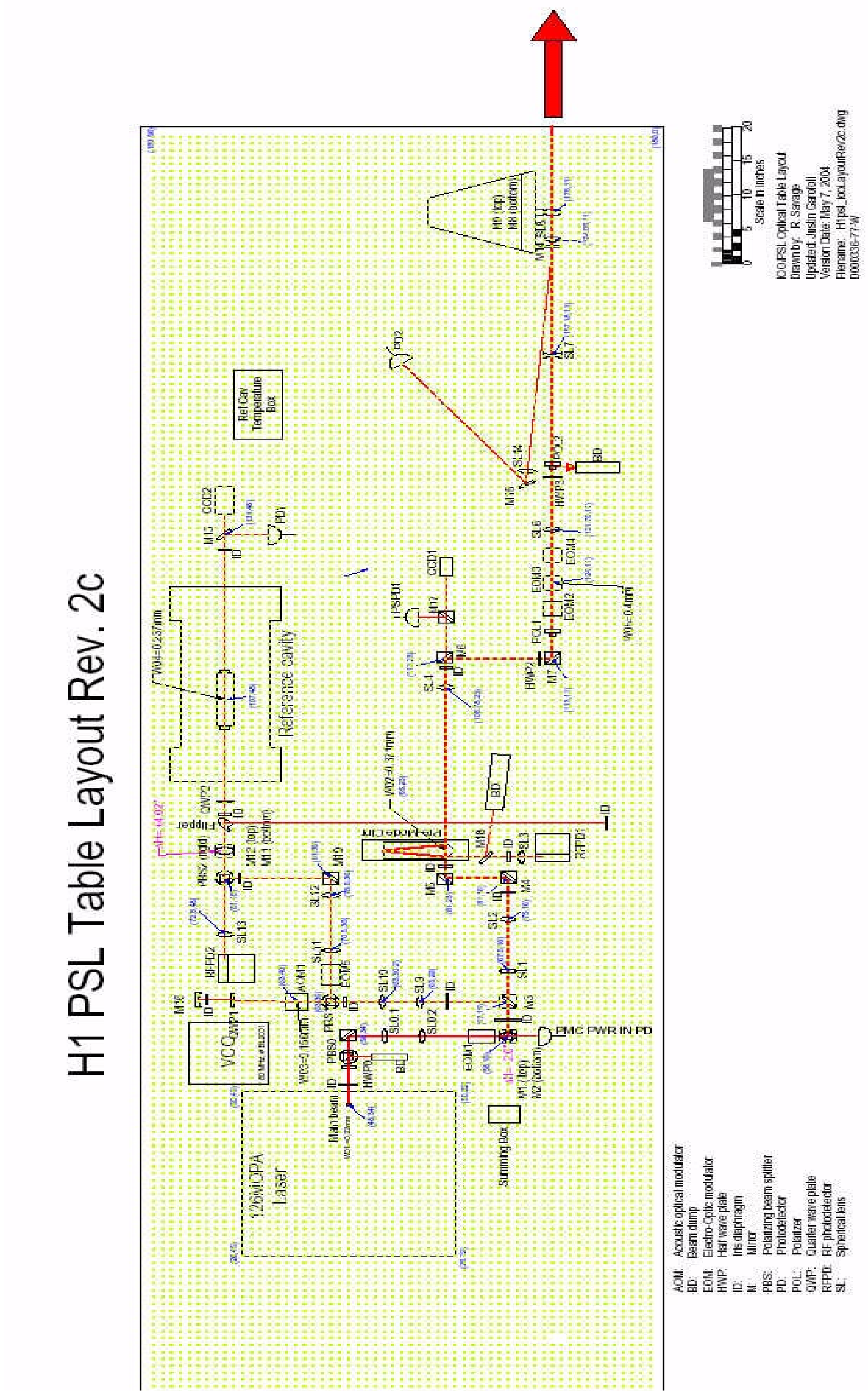


Figure 2: 4 km PSL ACAD Opto-mechanical Layout



4.2. Periscope

4.2.1. Resonances

Since the relative laser beam heights at the IOO/PSL table and at the input port of HAM1 has a 832 mm rise, a periscope is designed to raise the beam without change of the polarization of the light. The structure of the periscope has to maintain the stability of the supporting table and the lowest resonances have to be high enough to avoid amplification of ground noise. A newly designed periscope assembly has been implemented in all three LIGO IFOs (see D010231-00-D, K. Mailand). The top of the optical table (RS 4000 Table from Newport is assumed) has a typical maximum relative motion value of < 1.3×10^{-10} m (see Newport catalog). Predicted modes for the periscope by D. Coyne can be found in Table 13 below. The following are the modeling approximations:

1. Mirror & mount at the top are represented by box of equal weight and approximate size.
2. The interface to the optics table (mounting pads and bolts) are represented by pinned boundary conditions.
3. The close-out at the top of the vertical tube is omitted.

Table 13: Predicted Modes of the PSL/IOO table Periscope (D. Coyne 10/08/01)

Mode	*Hz*	*Description*
1	239	Symmetric bending (whole structure)
2	360	Left side bending, column torsion
3	373	Vertical extension/compression
4	421	Torsion
5	516	Assymetric side X-brace bending, column torsion
6	532	Symmetric side & rear X-brace bending
7	579	
8	604	
9	648	Symmetric 2nd bending
10	683	Rear X-brace, lower beam bending

Frequency spectra have been taken to compare the “old” periscope resonant frequencies with the resonant frequencies of this new periscope. These specra can be found in Figures 3 & 4 below.

Figure 3: The 2k LHO "new" periscope resonances as seen on the MC_F signal compared to the "old" periscope.

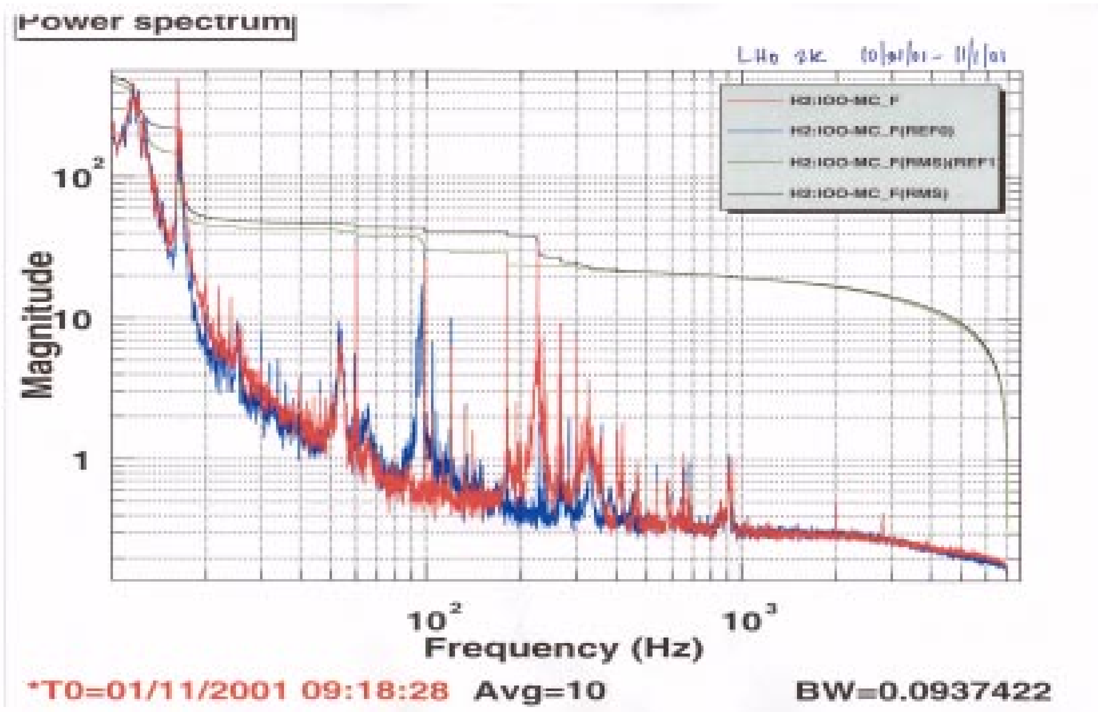
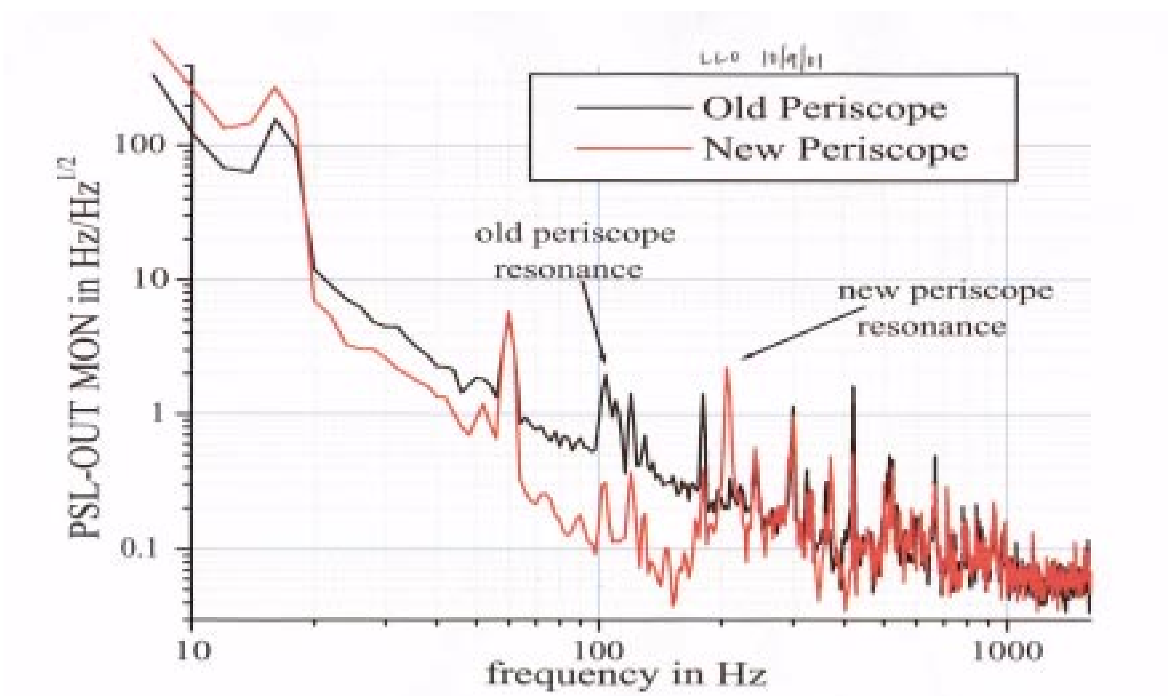


Figure 4: The 4k LLO "new" Periscope resonances as seen on the PSL_OUT signal, compared to the "old" periscope.



4.3. Beam Tube into HAMs

The periscope fits under the planned table cover. A hole is required in the cover for the exit beam, with either a nozzle (3-4 inch diameter TBD/PSL) or holes for a flange attachment. A tube protects the beam between the cover and the HAM viewport. A shutter with a lock is in place so that the PSL input beam can be lock-and-tagged out if needed.

4.4. In Vacuum Layouts

Complete in-vacuum layouts drawings for the 2k and 4k IOO subsystems are available on the DCC. Table 14 below lists the drawings.

Table 14: IOO HAM Table Layout Drawings in DCC.

IFO	*HAM*	*Drawing Number*
2k	HAM7	D000356
2k	HAM8	D000357
4k	HAM1	D000354
4k	HAM2	D000355

4.5. Baffles, Beam Dumps, and Wire Shields

The baffles located in HAM2 and HAM8 separating the IOO from the COC are provided by COS. Using analysis by COS, we have concluded that beam dumps for the beams which reflect off the vacuum feedthrough ports are not necessary. Should experimental findings or changes in the design dictate the necessity of beam dumps, space on the stacks has been provided. A list of what IOO Beam Dumps and Baffles have been installed so far can be found in Table 15 below (recall, the part numbers can be found in section 2.1 above).

After the wire failure of the 2k MMT2, due to burning by the laser beam, on June 28, 2002, wire shields were installed on the 2k MMT2 and MC2 suspensions. Before we could fit the rest of the IOO optics with similar wire shileds (scheduled for the “next vent”) we had another wire cutting incident. This time, the 2k RM REFL beam was steered onto the MMT1 suspension wire and the optic dropped onto it’s stops. This time, no magnets were broken, so the original MMT1 was rehung on HAM 7 in-situ during the June 19, 2003 vent. During this day vent, a proper (designed by COS) wire beam baffle was installed in front of the 2k MMT1. As well, OSEM cable connection baffles (also designed by COS) were also installed on HAM 7 cable assemblies.

The MC Baffle is an older baffle version and is being replaced by the more complete baffle package of errant baffles.

Table 15: IOO Beam Dumps and Baffles

Beam Dump/Baffle	*LHO 2k*	*LHO 4k*	*LLO 4k*
MC Baffle		X	
MC1 Errant Beam Baffle	X		X
MC2 Errant Beam Baffle	X	X	X
MC3 Errant Beam Baffle	X		X
MMT1 Errant Beam Baffle	X		X
MMT2 Errant Beam Baffle	X	X	X
MMT3 Errant Beam Baffle	X		X
FI Beam Dumps	X	X	X
Half Round Beam Tube Baffles	X	X	X
OSEM Cable Connection Beam Blocks	X	X	X

5 RF MODULATION SYSTEM

5.1. Design

The IOO RF modulation system must provide both the resonant and nonresonant sidebands required by the ISC subsystem. It also must provide an RF sideband for the mode cleaner length control. Three Pockels cells provide phase modulation of the carrier from the PSL.

The LIGO core optics require two modulation frequencies:

1. The first modulation frequency gives upper and lower sidebands that are resonant in the recycling cavity but not resonant in the interferometer arm cavities. These are used for controlling the lengths of the interferometer and for aligning the arm cavities and the beam splitter.

2. The second modulation frequency gives upper and lower sidebands that are not resonant in the recycling cavity. These are used for alignment of the recycling mirror.

The values of these frequencies are set by the lengths of the respective cavities. The resonant sideband frequency must satisfy

$$f_{res} = \left(k + \frac{1}{2}\right)\frac{c}{2L_{rc}}$$

where k = 0,1,2... and L_{rc} is the recycling cavity length. The extra factor of 1/2 occurs because the carrier is resonant in the arm cavities whereas the sidebands are not resonant in the arms, giving a extra 180^o phase shift in the reflectivity of the arms.

The nonresonant sideband frequency is chosen to miss the recycling cavity resonances. Both the resonant and nonresonant sidebands must be equal to one of the mode cleaner resonances, because the RF modulation is imposed before the mode cleaner. The resonant frequencies of the mode cleaner are:

$$f_{mc} = n\frac{c}{2L_{mc}}$$

where n is an integer (1,2,3...) and L_{mc} the mode cleaner length.

5.2. Constraints

The mode cleaner and recycling cavities span vacuum chambers whose separations determine the cavity lengths. There is some flexibility on account of the size of the optical tables in these chambers.[1] The mode cleaner for the 4-km interferometer occupies HAM1 and HAM2; the recycling mirror is in HAM3; the input test masses are in BSC1 and BSC3. The mode cleaner for the 2-km interferometer occupies HAM7 and HAM8; the recycling mirror is in HAM9; the input test masses are in BSC7 and BSC8.

In addition to the separations of the vacuum chambers, a number of factors affect the optical lengths of the mode cleaner and recycling cavities. These include the footprints of the suspensions, mirror thicknesses, the triangular path of the mode cleaner, substrate refractive index, the space required for other optical components, the offset of the optical centerline from the centerlines of the beam tubes, and the Schnupp asymmetry of the core optics. In addition, the modulation frequencies must miss all the harmonics of the arm free spectral range: 37.5 kHz in the 4-km interferometer; 75 kHz in the 2-km interferometer.

5.3. Resonant sidebands

5.3.1. Resonant sideband frequency

The RF frequencies for the resonant sidebands have been chosen according to the following criteria:

- The frequency must be consistent with the resonant cavity lengths described previously.
- The lengths of the two cavities (mode cleaner and recycling) shall not be an integer multiple of each other (so that harmonics of the nonresonant sideband do not resonate in the recycling

1. For details see M. Zucker and P. Fritschel, LIGO-T960122-00-I, D. Coyne, LIGO-T970068-00-D, D. Tanner, LIGO-T970XXX-03-D.

cavity).

- The frequency shall be as low as possible.

The frequencies and lengths for the two interferometers are in Table 16:

Table 16: Modulation frequencies for resonant sidebands and corresponding optical lengths.[a]

IFO	*n,k*	f_{res} (MHz)	L_{mc} (mm)	L_{rc} (mm)
4-km	2,1	24.482	12245	9184
2-km	3,2	29.486	15251	12715

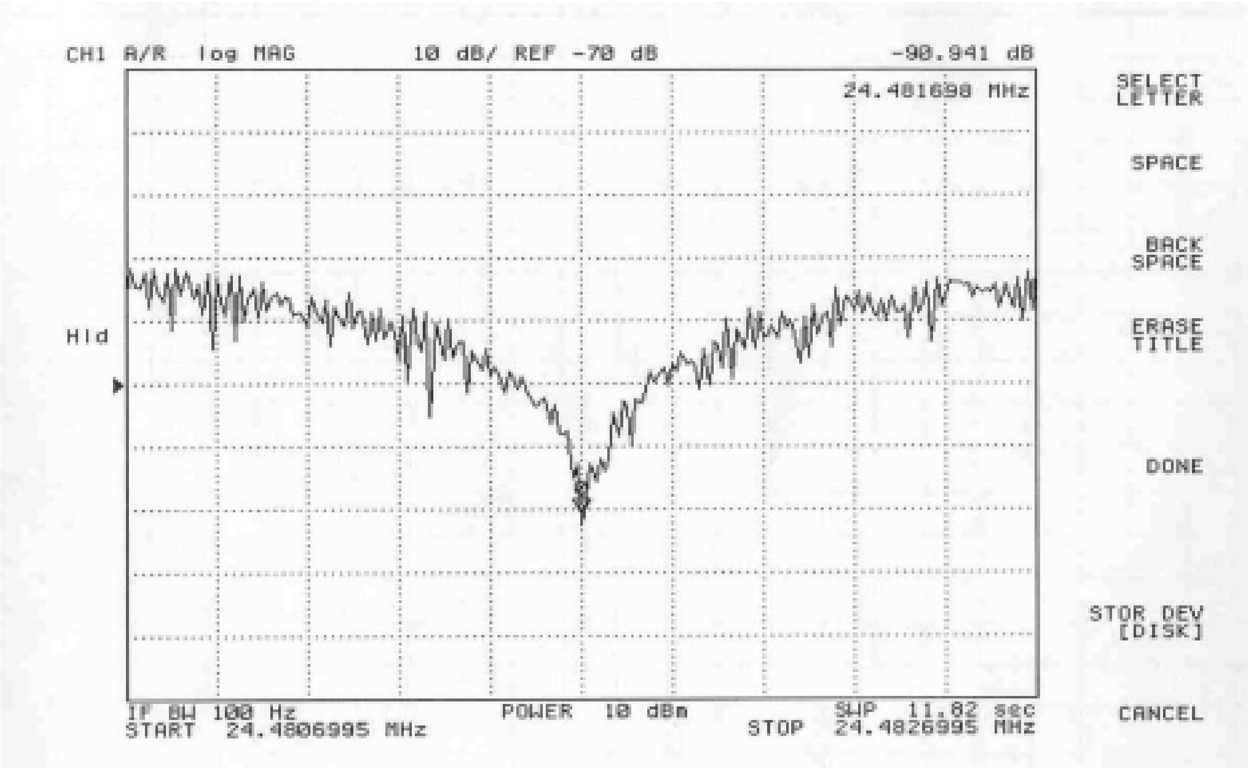
a. Updated numbers are from D. Coyne, E000053-02-D.

See the documents in footnote 1 for calculations justifying these frequencies.

5.3.2. 4k LHO Resonant Sideband Frequency Measurement

Figure 5 is the measurement of the 4k LHO MC Resonant Sideband Frequency that was made on 8/14/01. This frequency measurement corresponds to a MC half-length of 12245.15mm. This was verified by D. Sigg in his measurement of 12245.95mm, details in the Detector elog 2/15/2004.

Figure 5: 4k LHO Res. Sideband Frequency Measurement 8/14/01.



5.3.3. Pockels Cell

Phase modulation in a Pockels cell is achieved by electrically varying the optical path length of the light through an electro-optic crystal. The crystal must be aligned with the light polarization in order to avoid residual amplitude modulation to within 0.17^{o}. By using a resonant device, the RF drive voltages can be kept low. In this configuration, the 50Ω output of the RF amplifier is matched to the capacitive load of the crystal by a resonant circuit. Typical RF bandwidth is 1%, which is larger than the tuning range of the RF generators.

A suitable modulator is MgO:LiNbO3 (New Focus 4003) which has a phase shift of 0.2 rad/Volt. Thus, 4.7 V peak-to-peak is necessary for $\Gamma = 0.47$ and 10 V peak-to-peak for $\Gamma = 1$. The latter voltage implies a power load of 1/4 W RMS from the RF system.

5.4. Nonresonant sidebands

5.4.1. Nonresonant sideband frequency

The RF frequencies for the nonresonant sidebands have been chosen according to the following criteria:

- The frequency must be consistent with the mode cleaner cavity lengths described above.
- The frequency shall be sufficiently high that the effect of first-order mixing of the resonant and non resonant sidebands is reduced.
- The frequency shall not be an integer multiple of the resonant sideband frequency.
- The frequency shall be within the demonstrated range of the RF photodiodes (70 MHz TBD-ASC).

The frequencies for the two interferometers are in Table 17.

Table 17: Modulation frequencies for nonresonant sidebands.

IFO	n	f_{nr} (MHz)
4-km	5	61.204
2-km	7	68.851

5.4.2. Pockels Cell

The Pockels cell for the non resonant sidebands will be identical to the one used for the resonant sidebands (New Focus model 4003). The voltage for $\Gamma = 0.055$ is 0.6 V peak-to-peak, making the RF power required 0.9 mW RMS. The Pockels cell is capable of modulation indices up to $\Gamma = 1$ if 1/4 W RMS RF power is supplied.

5.5. Modulation for Mode Cleaner Length Control

5.5.1. Mode Cleaner Modulation Frequency

We.choose frequencies which have all harmonics nonresonant in the mode cleaner, and which have mixing sidebands with both resonant and nonresonant sidebands which are nonresonant in the mode cleaner.

Table 18: Modulation frequencies for mode cleaner locking.

IFO	f_{lock} (MHz)
4-km	33.289
2-km	26.717

5.5.2. Pockels Cell performance

The Pockels cell for the mode-cleaner sidebands will be identical to the one used for the other sidebands (New Focus 4003). The voltage for $\Gamma = 0.1$ is 1 V peak-to-peak, making the RF power required 2.5 mW. The Pockels cell is capable of modulation indices up to $\Gamma = 1$ if 1/4 W RF power is supplied.

6 MODE CLEANER

The mode cleaner serves several purposes in LIGO. It filters the non TEM_{00} components of the PSL output light, reduces amplitude and frequency noise of the light, contributes to frequency stability of the laser, decreases beam jitter (motion), and filters any incorrectly-polarized component introduced by the optics in front of it.

6.1. Optical Tolerances

Tables 19 and 20 list the optical parameters chosen for the mode cleaners. The 2k length *L* differs from the 4-km interferometers because of the differences in the separation of their HAM chambers. The parameters for the 2-km interferometer are then an appropriately scaled version of those for the 4-km interferometer. As-Built values in Table 19 were found in the elog. As-Built values in Table 20 were found in G000006 and in the elog.

Table 19: Optical parameters for the 4k mode cleaners

Item	*Unit*	4K IFO		*As-Built LHO*	*As-Built LLO*
Plane mirror transmittance		0.002	+/- 100ppm	2000ppm	
Plane mirror reflectance		0.998	+/- 100ppm		

Table 19: Optical parameters for the 4k mode cleaners

Item	*Unit*	4K IFO		*As-Built LHO*	*As-Built LLO*
Curved mirror transmittance		1E-05	+0, -10ppm		
Rear surface AR coating		>99.8%	+0.2%,-0		
Mirror absorbance/scattering	each	<0.00010		see E980140	
Finesse		1350			
Free spectral range	MHz	12.246			
Cavity full width/half max	kHz	7.83			
Cavity full width/half max	nm	0.342			
Cavity optical half-length	mm	12245.4		12245.15	12244
Curved mirror radius of curvature	mm	17250	+250,-350	17235	
g = 1 - L/R		0.290			
waist size	mm	1.629			
Raleigh range	m	7.83			
Beam divergence	μrad	208			
1 ppm intensity, curved mirror	mm	15.9			
100 ppm intensity, curved mirror	mm	13.0			

Table 20: Optical parameters for the 2K mode cleaner

Item	*Unit*	2K IFO	*Design*	*As-Built*
Plane mirror transmittance		0.002	+/- 100ppm	2255ppm
Plane mirror reflectance		0.998	+/- 100ppm	
Curved mirror transmittance		1E-05	+0, -10ppm	10ppm
Rear surface AR coating		>99.8%	+0.2%,-0	
Mirror absorbance/scattering	each	<0.00010		see E980139
Finesse		1550		1346

Table 20: Optical parameters for the 2K mode cleaner

Item	*Unit*	2K IFO	*Design*	*As-Built*
Free spectral range	MHz	9.829		9.836 (elog 6/01 D.G.)
Cavity full width/half max	kHz	6.26		7.31
Cavity full width/half max	nm	0.427		
Cavity optical half-length	mm	15251		
Curved mirror radius of curvature	mm	21500	+300, -400	+0,-500 (E970150)
g = 1 - L/R		0.291		
waist size	mm	1.818		
Raleigh range	m	9.76		
Beam divergence	μrad	186		
1 ppm intensity, curved mirror	mm	17.7		
100 ppm intensity, curved mirror	mm	14.5		

6.2. Physical Parameters

Detailed specifications of the 2 km, 4 km and 2 km MC mirror blanks can be found in LIGO-D970533, D970534,and D970535.

Detailed CAD drawings for the mirror blanks can be found in LIGO-D970536,37,38.

Detailed specifications for the substrates can be found in LIGO-E970146,44,43.

Detailed CAD drawings for the substrates can be found in LIGO-D970589,87,86.

Table 21 lists the mirror dimensions for the mode cleaners. The mirror size is set by the use of Small Optical Suspensions (SOS) in the mode cleaner. The coating diameter on the curved mirror is smaller than the physical diameter to provide additional clipping of higher-order modes, which spill over the coated area.

Table 21: Physical parameters for the Mode Cleaners

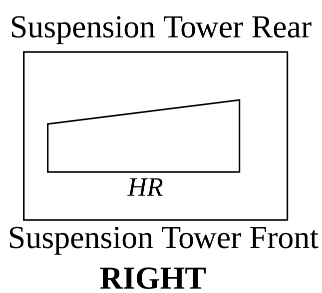
Item	*Unit*	*4k*		*2k*	
Mirror thickness (at max thickness)	mm	25	+0, -.5	25	+0, -.5

Table 21: Physical parameters for the Mode Cleaners

Item	*Unit*	*4k*		*2k*	
Mirror wedge angle	mrad	8.73	+0.15, -0 mrad	8.73	+0.15, -0 mrad
Mirror diameter	mm	75	+1, -0	75	+1, -0
Coating diameter (curved mirror)	mm	25		28	
Flat mirror radius of curvature	km	>80		>80	
Coating diameter (flat mirrors)	mm	70		70	

6.2.1. Wedge Orientations

The Mode Cleaner optics all have horizontal wedges, with their thick sides noted to be either "left" or "right." *The convention is defined such that the "left" and "right" refer to the orientation of the thick side of the optic when viewed from above:*



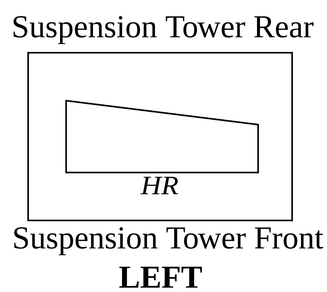


Table 22: Wedge Orientations of the Mode Cleaner Optics

Mirror	*Design 2k & 4k*	*4k LHO*	*2k LHO*	*4k LLO*
MC1	Thick side Right	Left	Right	Left
MC2	Thick side Left	Left	Left	Left
MC3	Thick side Left	Left	Right	Right

6.2.2. Serial Numbers

Table 23: Serial Numbers of the MC Optics

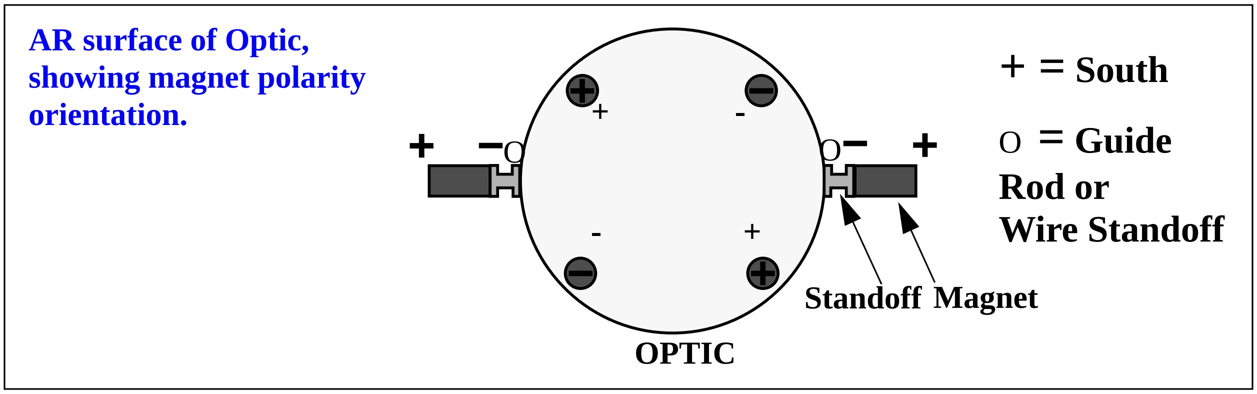
Optic	*2k LHO*	*4k LHO*	*4k LLO*
MC1	MCFM08-1	MCFM02-1	MCFM03-1
MC2	MCCM2k01-1	MCCM4k03-1	MCFM05-1
MC3	MCFM09-1	MCFM07-1	MCCM4k02-1

6.2.3. Magnet Polarity Configurations

The polarities of the magnets bonded to the optics were intended to be bonded with specific polarities of the magnets facing away from the optic. When looking at the back (AR) surface of the optic (and with the top of the optic at the top), the magnets should have the South seeking end exposed on the Upper Left, Lower Right, and both Side magnets. North seeking magnets should be on the Upper Right and Lower Left of the optic. See the figure below for a schematic of this.

Table 24: As-built SOS magnet polarities.

Optic	*2k LHO*	*4k LHO*	*4k LLO*
MC1	Inverted	Inverted	Normal
MC2	Inverted	Normal	Normal
MC3	Normal	Normal	Normal
SM1	Inverted	Normal	Normal
SM2	Normal	N/A	N/A
MMT1	Normal	Normal	Normal
MMT2	Normal	Normal	Normal
MMT3	Normal	Normal	Normal



6.2.4. Suspension Wire

At Hanford, a spool of Molybdenum wire of the same SOS wire thickness was inadvertently used to suspend some of 4k SOSs. This was not discovered until the 4k IFO was pumped down and MC measurements were being performed. To compound the problem, the 4k MC1 and the 2k MC3 were swappped during the 2/28/01 Earthquake repairs. Which MC optics are suspended with which type of wire can be found in Table 25.

Table 25: Wire material used for suspensions

Mirror	*Design 2k & 4k*	*4k LHO*	*2k LHO*	*4k LLO*
MC1	Steel Music Wire	Steel Music Wire	Steel Music Wire	Steel Music Wire
MC2	Steel Music Wire	Molybdenum Wire	Steel Music Wire	Steel Music Wire
MC3	Steel Music Wire	Molybdenum Wire	Steel Music Wire	Steel Music Wire

See Stan Whitcomb’s LHO Detector Elog Entry of 9/20/01 about this issue.

6.2.5. Resonances

6.2.5.1 Bounce Mode Measurements

Figure 6: High resolution spectrum of 4k MC_F signal showing bounce mode at 16 Hz.

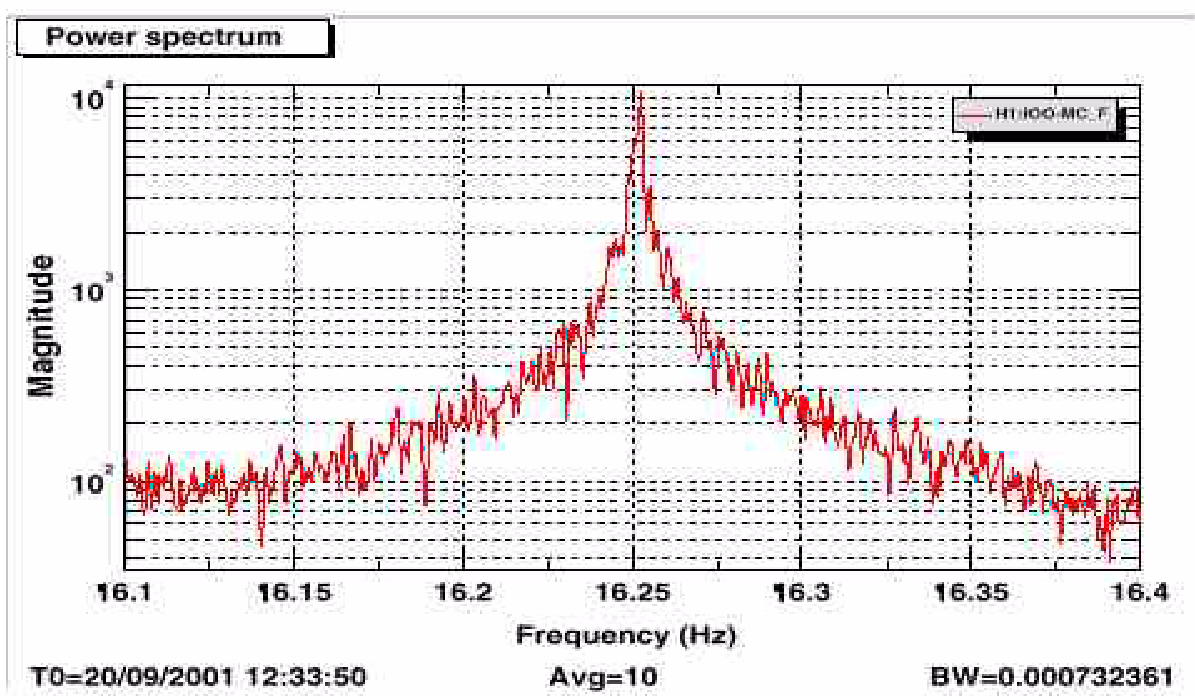


Figure 7: High Resolution Spectra of 4k SOS sensors, showing only MC1 peaking at16Hz.

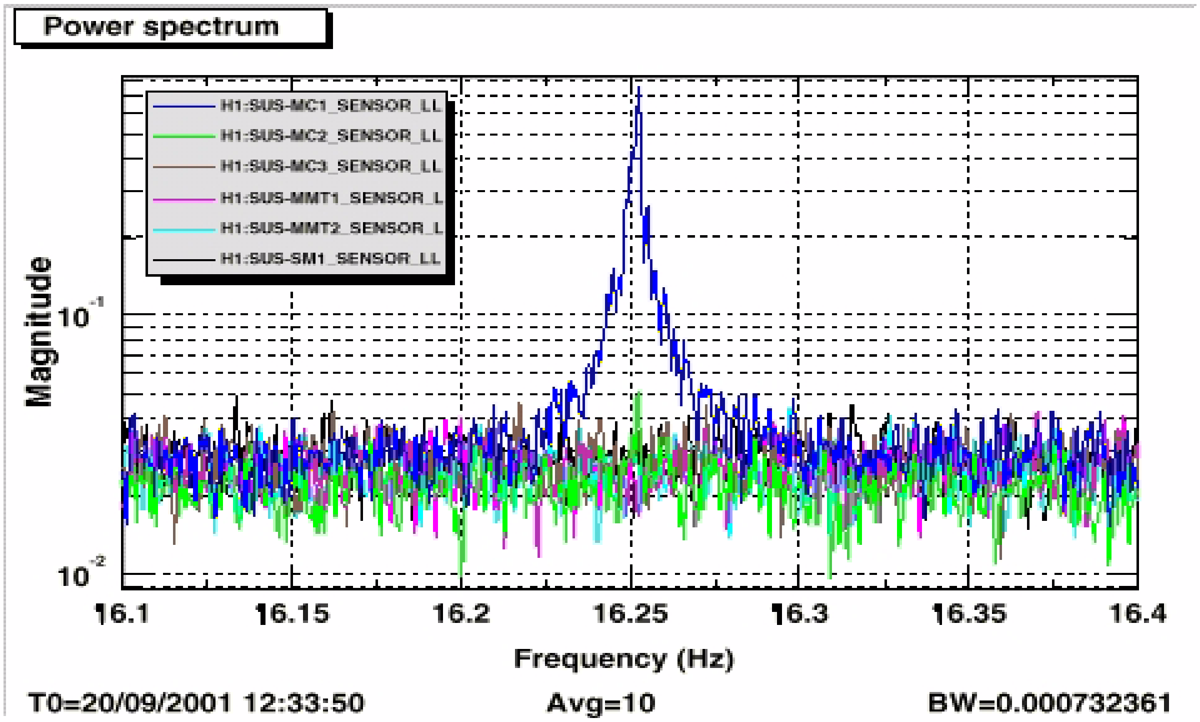


Figure 8: Coherence spectra of 4k SOS bounce modes at 19Hz instead of 16Hz.

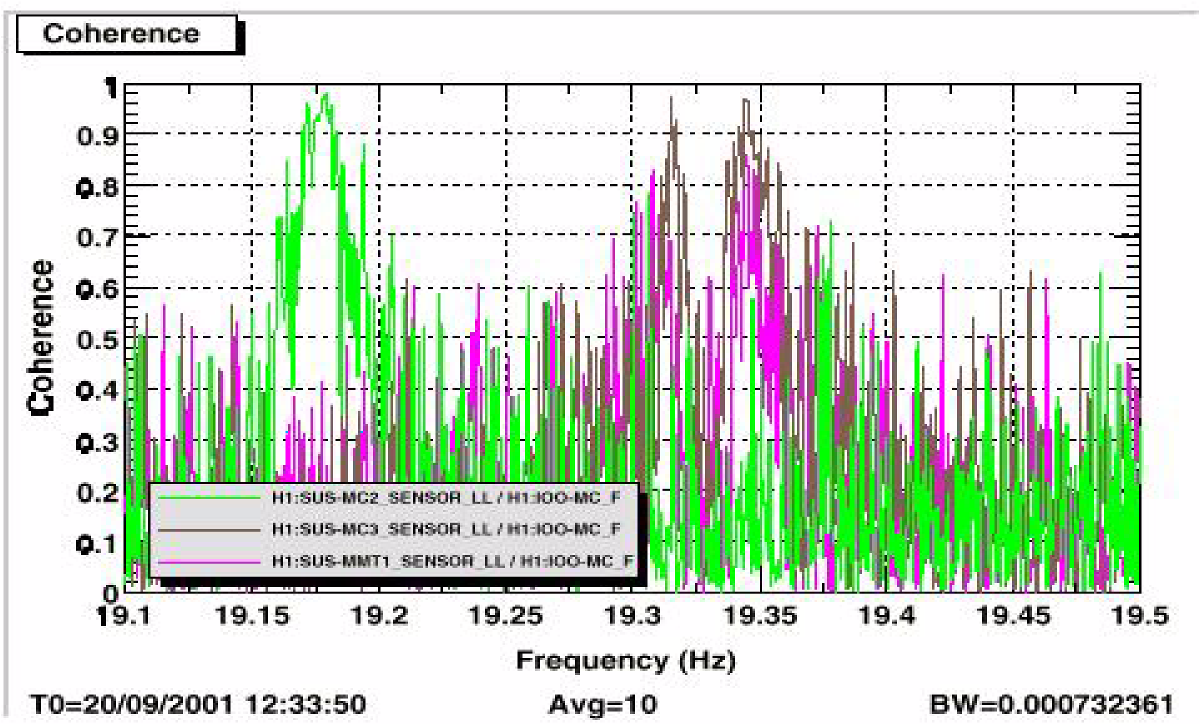


Figure 9: Coherence spectra of 4k MC1 and MC3 with MC_F at 16Hz.

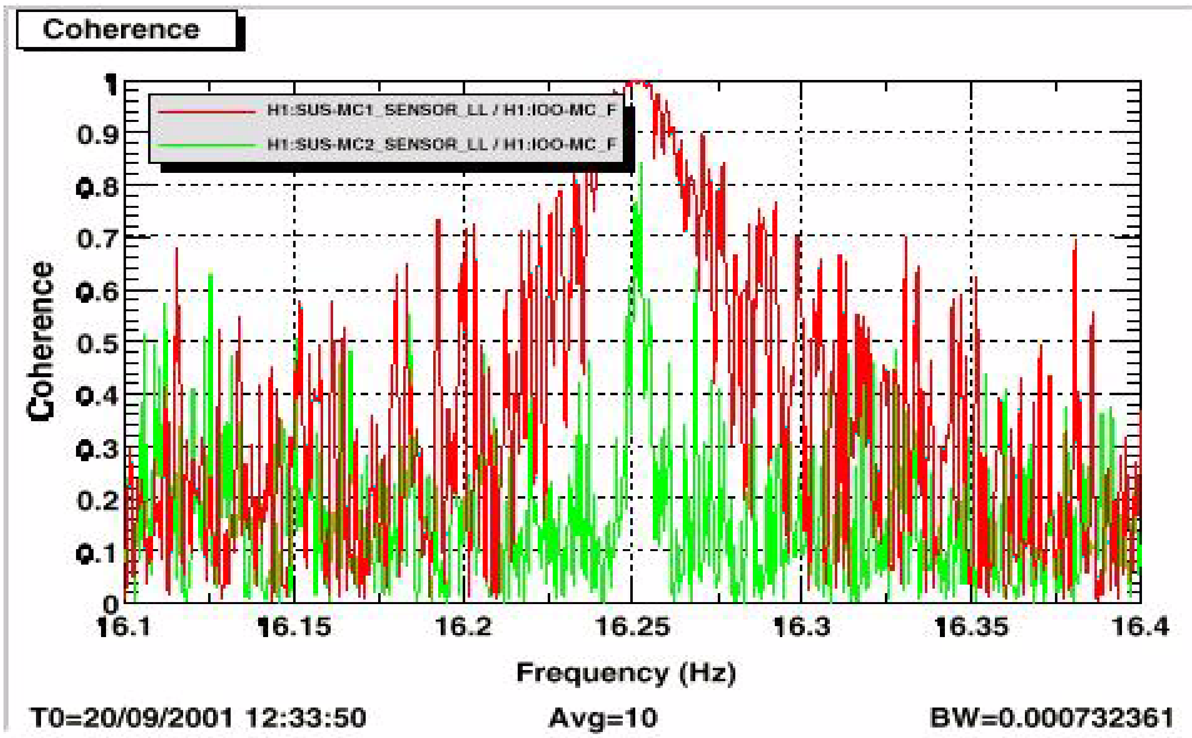


Figure 10: Spectra of MC_F and 4k SOS sensor signals in the 19Hz region.

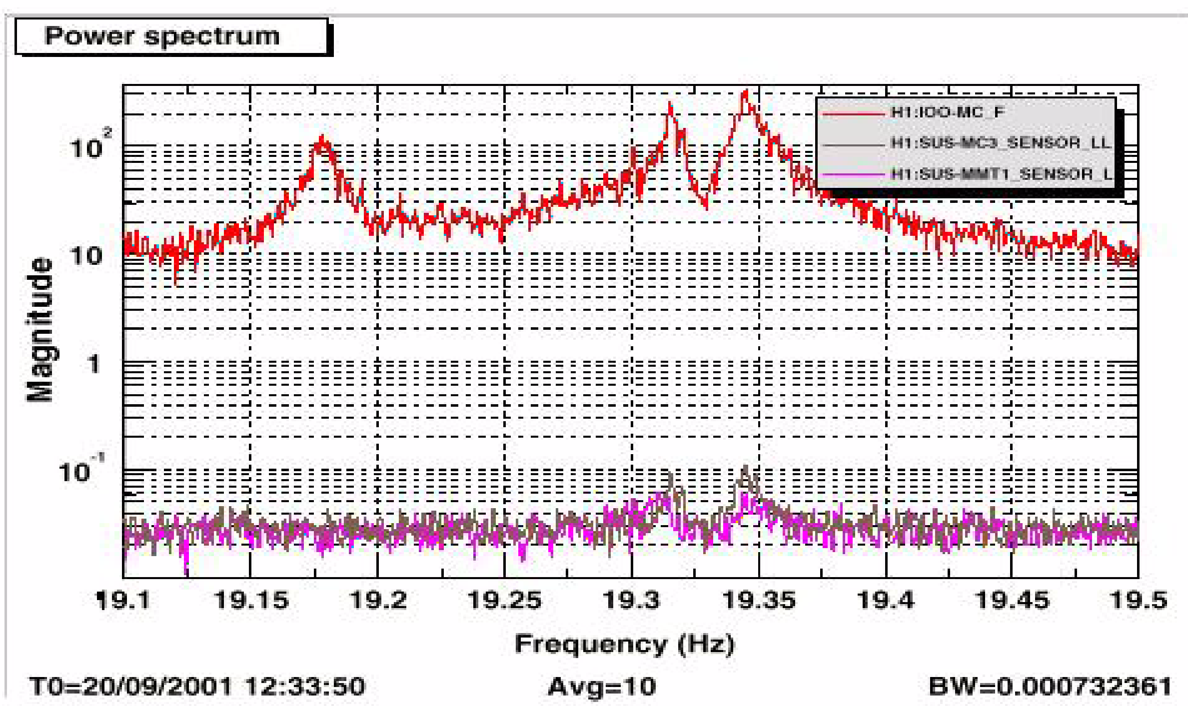
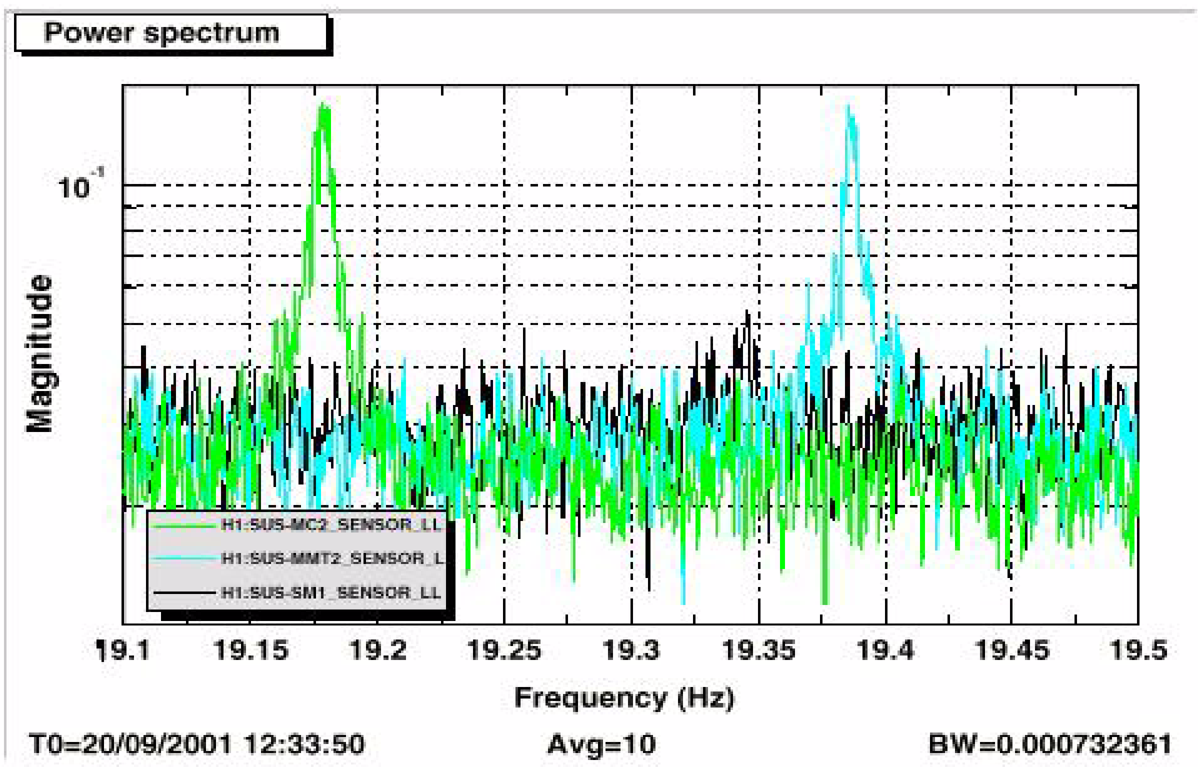


Figure 11: Spectra of the 4k MC2, MMT2, and SM1 19Hz bounce mode.



6.2.5.2 Internal Modes

Table 26: 2k MC Internal Modes Measured - see G000006, P. Fritchel

Mirror	*Mode f (kHz)*	*Q (10^6)*
MC1	28.233	0.75
MC2	28.199	0.37
MC3	28.233	1.29

Table 27: 4k LLO MC Internal Modes Measures - see LLO elog Aug 2, 2001

Mirror	*Mode f (kHz)*	*Q (10^6)*
MC1	28.165	0.15
MC2	28.208	0.29
MC3	28.238	0.07

6.2.6. MC2 Riser

Because of the difference in LIGO local and global coordinates a riser is installed under the MC2 suspension to position MC2 at local level with MC1 and MC3. The riser for the 2k MC2 is 8.5mm in height.

6.3. Mode Cleaner Length and Alignment Requirements

6.3.1. Allowable sideband detune from resonance

Allowable sideband detune from resonance: 100 Hz

This requirement was derived to hold RF oscillator phase noise to amplitude modulation after the mode cleaner at the level of 10^{-8} / rHz[1]. For a given modulation frequency, this sets the initial length position tolerance.

6.3.2. Mode Cleaner Alignment

Low frequency: beam jitter -> frequency noise must be kept below mode cleaner thermal noise, requiring $\theta_{rms} < 3 \times 10^{-7}$ rad[2] (at 100 Hz). The following is an exerpt from the LHO Detector elog of June 17, 2001 by P. Fritchel regarding 2k MC fluctuations. The measurment was made at the output of the MC, and after they had tuned up the MC controller settings:

> Beam radius at detector: 2.14 mm
>
> Sum voltage: 0.66 V
>
> Distance from MC waist: 6 m
>
> Position sensitivity: 0.66V*1.13*10/2.14mm = 3.5 V/mm
>
> Quad signals: approx. 10 mV rms for horizontal & vertical
>
> Position fluctuations: 2.7 um rms, horiz & vert
>
> *Equivalent angle fluctuation, from MC waist: 0.45 urad rms*”
>
> - peterF

And the note attached to the elog:

> It’s worth noting that the ~0.5 urad angle fluctuations at the MC output get reduced by the mode matching telescope by a factor of about 20, to 2.5e-8 rad. Of course, the SM and mode matching telescope optics are adding pointing fluctuations too.
>
> - peterF

1. Length Sensing and Control Design Requirements Document, T960058
2. see (1) above

6.3.3. Mode Cleaner Beam Centering

The beam spot must be centered in the mode cleaner mirrors to a precision of 1 mm to avoid length-misalignment couplings.[1] This sets the initial angular position tolerance.

6.3.4. Initial Optics Positioning Requirements

These requirements sets the positioning tolerance of the 2 km and 4 km MC as follows:

Table 28: Mode Cleaner Alignment Requirements

Parameter	*Value*	*Tolerance*
2 km MC Half Cavity Length	15.251 m	**+/- 1000 μm**
2 km Angular Tolerance		**+/- 200 μrad**
4 km MC Half Cavity Length	12.245 m	**+/- 1000 μm**
4 km Angular Tolerance		**+/- 200 μrad**

6.4. SOS Installation and Alignment Procedure

The initial alignment begins with the installation of the in-vacuum chamber components. For the mode cleaner, we will need to know the separation of the tables in HAM7-8 and HAM1-2 to 1 mm. ASC is to provide position information in the chambers, such that a fiducial point on an optical component can be located to this distance. (The distance between the inside edges of the tables at two points separated by the diameter of the beam tube connecting them would be the most convenient.) Once this position is known, the following procedure will be used (Although we specify 2 km MC alignment procedures here; the method is applicable to the 4 km IFO):

1. The PSL will provide a 50 mW beam to the IOO which will be directed into the HAM7 through viewport WH7B2F3 (or the equivalent viewport on HAM1 for the 4k). The input polarization of this beam will need to be rotated to horizontal using a half wave plate positioned at the base of the telescope. This is done to increase the transmittance through MC1 and MC3.
2. Clamp MMT3 with it's safety stops. (MMT3 was installed prior to IOO installation in HAM7 and 8.)
3. Using 2 Beam Height Targets, one at either end of the table along the designed line of table holes (see HAM7 table layout drawings), in HAM7, the pointing of the PSL beam is adjusted with the M1 and M2 periscope mirrors so that the beam propogates through both target holes. This places the beam at 5 &1/2 inches above the HAM 7 table.
4. The PSL/HAM7 light pipe shutter should be closed for personel safety during Steps 5-12.
5. On the PSL table,mount an iris on the PSL enclosure door that marks the location of the beam as it leaves the PSL table. This served as one of our two beam pointing feducials into the MC.

1. Alignment Sensing and Control Requirements Document, LIGO-T952007-03-I

6. With all optics clamped in their towers, install MC3, MC1, SM1, SM2, and MMT1 (in that order) using dead-reckoning, based on the table hole pattern. Removed the corresponding counterweights for each tower as it is installed.
7. Next, install the Faraday Isolator and all Steering Mirrors on HAM7.
8. Relevel the HAM7 table by repositioning the counterweights.
9. Install MMT2, MC2, their risers, and all Steering Mirror components in HAM8. Again, counterweights should be removed to maintain load and level of the table. MC2 needs to be installed to within 1mm of it's designed position on HAM8.
10. Place alignment iris bars on all of the HAM 7 SOSs. (Double holed irises for MC1, MC3, SM1, and SM2. Single holed iris targets for MMT1, MMT2, and MC2.)
11. Place a Beam Height Target after MC3, in line with the SM1, MC1, and MC3 centers.
12. Adjust the first rigid Steering Mirror before the MC in pitch and yaw to center on both the MC1 iris target and the Beam Height Target behind MC3.
13. Open the PSL/HAM7 light pipe shutter, letting the beam propagate into the MC.
14. **MC3 alignment:** MC 3 should be released from its stops and damping should be activated. The spot reflected from the input beam incident on MC 3 should be located in the vicinity of MC2. Once this is found, MC3 should be steered using ASC pitch biases until the beam in centered on MC2. If the ASC yaw bias required to do this exceeds 0.5 units, the tower must be rotated such that this beam is incident on the center of MC 2 with less than 0.5 units of yaw bias. To do this it is useful to set up a CCD camera to look at the face of MC2.
15. Reclamp all optics, and clamp two pusher bars down with dog clamps, to push on the tower base surfaces in a rotating direction. Unclamp MC3. Using the pushers on MC3, the MC3 gently twist the tower until the beam reflected from MC3 is centered on the MC2 centering iris. Care should be taken so that the tower is translated only a negligible amount. **Note:** Each time dog clamps are installed or removed, all optics on the HAM table must be clamped for safety!
16. **MC2 alignment:** Ensure that the beam propogating from MC 3 is centered on MC 2. Release MC2 from its stops and activate damping of MC2. Check for the spot reflected from MC 2 in the vicinity of MC1. MC2 will then be adjusted using SOS actuators to retroreflect the beam back to the target on MC1. Once this is found MC2 should be steered using ASC pitch biases until the beam in centered on the outer iris mounted on MC1. If the ASC yaw bias required to do this exceeds 0.5 units, the tower must be rotated such that this beam is incident on the aperture of MC 1 with less than 0.5 units of yaw bias. See Step 15 above for rotating towers. To do this it is useful to set up a camera looking at the iris on MC1.
17. **MC1 alignment:** Ensure that the beam propogating from MC 2 is centered on MC 1. Release MC1 from its stops and activate damping of MC1. Check for the spot reflected from MC 1 in the vicinity of MC2. Once this is found, MC1 should be steered using ASC pitch biases until the beam in centered on MC 2. If the ASC yaw bias required to do this exceeds 0.5 units, the tower must be rotated such that this beam is incident on the aperture of MC 1 with less than 0.5 units of yaw bias. Again, see Step 15 above for rotation of towers.
18. **Fine tuning the alignment:** Set-up a camera looking at the front face of MC2 and another camera looking at a target that the beam exiting the mode cleaner falls onto. Tweak the alignment of MC3 such that the beam striking MC2 is centered. Tweak up the alignment of MC2 such that the first round trip spot overlaps the straight through spot as observed near the output of the mode cleaner. Tweak the alignment of MC1 to get maximum brightness of the flashes.
19. **Align modecleaner reflected and transmitted port monitors:** Using the Viewport/HAM

Door Target Fixture designed by Ken Mailand.

20. **Set the MC Transmission, Reflection, and Periscope pointing alignment fiducials:** Re/ mark the wall with the Reflected beam. Double check the pointing of the Input beam from the PSL through the input iris.
21. **Alignment of Mode Matching Telescope:** Record the bias of MC2 when the mode cleaner is aligned, then deliberately misalign by setting the yaw bias to -10.
22. In order to align the MMT, the first half-wave plate in the Faraday Isolator assembly must be rotated to maximize the transmission through the Faraday for Horizontally polarized light.
23. Align SM1 as per the sequence in Steps 14 and 15 above, to the centering target on SM2.
24. Align SM2, then MMT1, and then MMT2 as per the sequence of Steps 17 and 18 above, SM2 to center the beam on the MMT1 target, MMT1 to center the beam on MMT2, and MMT2 to center the beam on MMT3.
25. At this point, the COS alignment will use the COS alignment laser to trace the beam path from the IFO back through MMT3, to MMT2. MMT3 will be fine-aligned such that the COS alignment beam is centered on MMT2. A fine-alignment of MMT2 should be done such that spot reflected of the RC retraces itself and is rejected out of the Faraday.
26. Monitor the Sensor/Actuator voltages throughout this procedure. If the voltages are measured to be outside of the range of -1.25V to -0.75 V, the Sensor/Actuator heads must be adjusted back to within this range. Many of the above steps in this procedure will need to be repeated once this is done, as the alignment will probably now be off.
27. Adjust the first half wave plate such that the light transmitted through the Faraday is minimized. This will set the light incident on the Faraday to the correct polarization when the half wave plate at the base of the IO periscope is removed.
28. At this point, the alignment jigs and positioning tooling will be removed. The alignment tolerances of 200 μrad and 1 mm should be adequate to achieve lock. It is anticipated, however, that vacuum pumpdown of the HAMs will shift the stacks by as much as 2 mm and will cause some misalignment of the MC. The pilot beam will remain to allow re-adjustment of the MC2,3 pitch and yaw to regain the necessary alignment tolerance. At this point the MC should be locked.
29. Once lock is achieved, the WFS will align the MC to the required locked angular alignment. A measurement of the FSR of the MC will be performed to determine the length. If the measurement indicates that the pump down shifts have pushed the mirrors beyond the range of the SOS actuators, HAM8 will be re-opened and MC2 repositioned to compensate for the shift. Pump and lock will proceed as in 8).

7 IN-VACUUM FARADAY ISOLATOR

A Faraday Isolator positioned between the mode cleaner and the mode-matching telescope serves to divert the back-reflected interferometer light out to ISC photodiodes for IFO diagnostics. The presence of the FI in the vacuum impacts IOO design considerations from a number of standpoints:

- Vacuum Contamination
- Stray B-field coupling to SOS magnets
- Thermal lensing in the FR

In June 2004, a new Faraday Isolator was installed on HAM7, replacing the existing FI. Unacceptable problems were found with the older version of the FI such as clipping and beam drift due to thermal heating of the FI components. The newer FI design incorporates a larger aperatured Faraday rotator and spreads the components further apart so visuals can be made regarding clipping. As well, a beam that was previously dumped on the FI, now exits the vacuum system for diagnostic purposes.

7.1. Mechanical Layout

See E040431 for schematic of new 2k Faraday Isolator and beam layout into ISCT7 since June 2004 installation.

7.2. Alignment procedure

The newest 2k Faraday Isolator (post June 2004) was assembled and aligned in the LHO optics lab as per E040128.

As described by Stan Whitcomb in LIGO-T030134-00-W, the 4k FI was aligned as per the following procedure:

1. Rotate the first polarizer to be perpendicular to local horizontal using a buble level, to within about 1 mRad.

2. Rotate the second polarizer to minimize the rejected light (parallel to the first polarizer).

3. Insert the Faraday body and the half-wave plate.

4. Rotate the half-wave plate to minimize the back transmitted beam (using a retro-reflecting mirror).

5. Rotate the first and second polarizers around their vertical axis to maximixe the power transmission through the FI assembly.

6. Iterate through steps 4 and 5 above.

7.3. 2k LHO Results

As described by David Reitze in LIGO-T030134-00-W, the original 2k (pre June 2004) Faraday Isolator measured to have 91% Transmission Throughput and 0.00069 Rejection Ratio.

The new FI measured by Malik Rakhmanov (LHO Detector elog 7/1/04) on the bench to have 98.7% Throughput and a 0.000125 Isolation.

7.4. 4k LHO Results

As described by Dave Ottaway in LIGO-T030134-00-W, the 4k Faraday Isolator measured to have 87% Transmission Throughput and 0.0001 Isolation.

8 SUSPENDED STEERING MIRRORS

8.1. Physical Parameters

8.1.1. Wedge Orientations

See Section 6.2.1 for more information.

Table 29: Wedge Orientations of the SOS Suspended Steering Mirrors in the 2k and 4k IFOs.

Optic	*Design*	*2k LHO*	*4k LHO*	*4k LLO*
S1	Left	Left	Left	
S2	Left	Left	NA	NA

8.1.2. Serial Numbers

Table 30: Serial Numbers of the SOS Suspended Steering Mirrors in the 2k and 4k IFOs.

Optic	*2k LHO*	*4k LHO*	*4k LLO*
S1	SM04-1	SM01-1	SM03-1
S2	SM07-1	NA	NA

8.1.3. Magnet Polarity Configuration

See magnet Polarity Configuration Section 6.2.3 above for more information.

Table 31: Magnet Polarity Orientations as Installed

Optic	*2k LHO*	*4k LHO*	*4k LLO*
S1	Inverted	Normal	
S2	Normal	N/A	N/A

8.1.4. Suspension Wire

See Suspension Wire Section 6.2.4 above for explanation of Molybdenum Wire usage.

Table 32: Suspension Wire used on the SOS Suspended Steering Mirrors in the 2k and 4k IFOs.

Optic	*2k LHO*	*4k LHO*	*4k LLO*
S1	Steel Music Wire	Molybdenum Wire	Steel Music Wire
S2	Steel Music Wire	NA	NA

9 IFO MODE MATCHING TELESCOPE

9.1. Mode Matching Optics

The mode matching into the mode cleaner is done with a three refractive lens design. The constraints on the problem were that the lenses need to lie on the IO/PSL table, match the waist in the Pockels cells to the waist of the mode cleaner, use standard optics available through a vendor, and offer a wide range of adjustment.

An addtional constraint was imposed during commisioning that the total length of the mode-matching chain was less than 1.5m from the center of the middle EOM to the last lens. This was added so that the number of reflective components on the PSL/IO table could be reduced. The PSL to IO hand off point was redefined to be the waist formed by the PMC. This was done to further reduce the optical pathlength of the PSL/IO chain and reduce the number of reflective components on the optical table, which have all been found to be sources of frequency noise. The details of the design of the modematching from the PMC to the main mode cleaner have been outlined elsewhere and the parameters are included here for completeness:

Table 33: Mode matching into the Mode Cleaners

Parameter	*4k Value*	*2k Value*
Waist size in the PMC	0.371 mm	0.371 mm
Distance to PMC to lens f_{EOM}	596.5 mm	596.5 mm
Distance from f_{EOM} to entrance EOM_1	562 mm	562 mm
Distance from exit EOM_3 to f_1	68.5 mm	68.5 mm
Distance from f_1 to f_2	645 mm	655 mm
Distance from f_2 to f_3	429mm	419 mm
Distance from f_3 to MC waist	4900 mm	3300 mm
Waist size in MC	1.629 mm	1.818 mm

Table 33: Mode matching into the Mode Cleaners

Parameter	*4k Value*	*2k Value*
Nominal focal length of f_1 (focal length for 1064 nm)	400 mm (458.2 mm)	400 mm (458.2 mm)
Nominal focal length of f_2 (focal length for 1064 nm)	-200 mm (-229.1 mm)	-200 mm (-229.1 mm)
Nominal focal length of f_3 (focal length for 1064 nm)	500 mm (572.7 mm)	500 cm (572.7 mm)

The adjustablility of the telescope is explored in LIGO Document T010004-00-W . The telescope can easily vary the size of the waist by +/- 10 % while holding the waist position constant. It can also adjust for +/- 10% changes in the position of the waist whilst holding the position of the waist constantin either the MC waist or the waist in the pockel cell of 10% easily.

The lensing properties of the EOMs have been carefully studied, despite this they remain the least accurately known parameter in the modematching chain. The modematching chain has been designed to incorporate a good estimate of the thermal lens properties of the EOMs. However enough adjustability in the telescope has been included so that small variations can be nulled out. In practice a modematching of 98% has been achieved for both the 2km and 4km interferometers.

9.2. Expected variations in COC and IOO parameters

Variations from nominal design and operation of the COC and IOO optical components can lead to a reduction in mode-matched power to the COC. Expected deviations which may reduce coupling efficiency include:

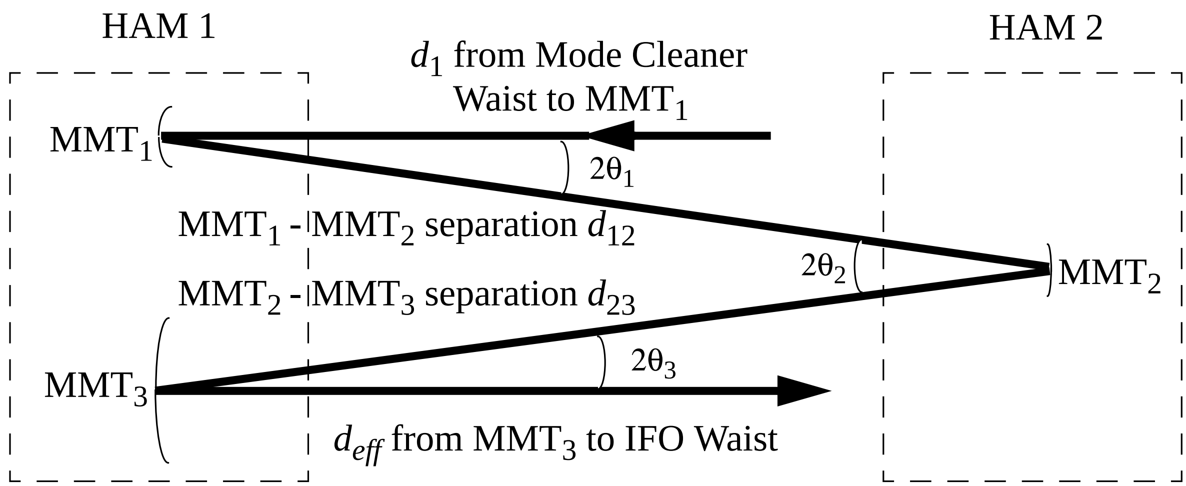
- Thermal distortions in COC, mode cleaner, Faraday isolator
- Surface figure errors in polishing of IOO and COC mirrors
- Long term stack drift
- Pump down shifts in the stack positions

9.3. MMT Optical Design

The LIGO IFO mode matching telescopes (MMT) will use a three element reflective spherical mirror design. Our design allows for optimization of mode-matched power by having independent adjustment of two degrees of freedom (waist size and position or, alternatively, wavefront radius of curvature and beam divergence angle) over a wide range of modal space.

Figure 12 shows the conceptual layout and definition of parameters. Table 34 lists the input parameters used in the design.

Figure 12: Definition of Parameters



Analytical details of the design can be found in *Design Considerations for LIGO Mode-Matching Telescopes, LIGO-T970143-00-D*. Briefly, we analytically solve for *all* possible radii of curvature (R_{MMT1}, R_{MMT2}, R_{MMT3}) which mode-match to the Fabry-Perot cavity. We then use optimization to select the set which provides the *maximum* amount of adjustment of waist size and position in the core optics. The optimal values for (R_{MMT1}, R_{MMT2}, R_{MMT3}) for both the 2 km and the 4 km IFO are shown in Table 34.

Table 34: Parameters for the 4km and 2km IFOs

	Units	4k Design	2k Design
w_0 = Waist size in Mode Cleaner	cm	0.1629	0.1818
d_1 = Dist. from MC waist to MMT_1	m	1.436	3.159
d_{12} = Dist. from MMT_1 to MMT_2	m	13.72	13.41
d_{23} = Dist. from MMT_2 to MMT_3	m	14.45	13.78
d_{rm} = Distance to recycling mirror	m	16.18	17.22
w_{eff} = Effective waist size in arms	cm	3.16	2.94
d_{eff} = Effective waist position in arms	m	1692	1161
w_3 = Waist size in arm	cm	3.51	2.56
d_3 = Waist position in arm from ITM	m	975	615.8
θ_1 = Incident angle on MMT_1	mrad	71.6	96.2
θ_2 = Incident angle on MMT_2	mrad	6.8	13.2

θ_3 = Incident angle on MMT_3	mrad	5.9	6.8
w_{m1} = Spot size on MMT_1	cm	0.169	0.195
w_{m2} = Spot size on MMT_2	cm	0.365	0.302
w_{m3} = Spot size on MMT_3	cm	3.65	3.23

Detailed specifications for the mirror blanks can be found in LIGO-D970533,34,35. (incorrectly assigned D numbers)

Detailed CAD drawings for the mirror blanks can be found in LIGO-D970536,37,38

Detailed specifications for the substrates can be found in LIGO-E970146,44,43.

Detailed CAD drawings for the substrates can be found in LIGO-D970589,87,86

9.4. 2 km IFO MMT at LHO

9.4.1. Optical Component Specifications

Table 35: 2 km MMT1 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Front Surface Radius of Curvature	11.28 m[a]	$\pm 0.1 m$
Diameter	75.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	25. 0 mm	+ 0 mm, - 0.5 mm
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Reflectivity	> 0.99	
Wedge Orientation (see Sec. 6.2.1)	Left	
Serial Number	MMT12k01-1	
Magnet Polarity (see Sec. 6.2.3)	Normal	
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Specified value - Actual value not yet measured.

Table 36: 2 km MMT2 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Front Surface Radius of Curvature	2.1 m[a]	$\pm 0.04 m$
Diameter	75.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	25. 0 mm	+ 0 mm, - 0.5 mm
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Reflectivity	> 0.99	
Wedge Orientation (see Sec. 6.2.1)	Left	
Serial Number	MMT22k02-1	
Magnet Polarity (see Sec. 6.2.3)	Normal	
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Specified value - Actual value not yet measured.

Table 37: 2 km MMT3 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Front Surface Radius of Curvature	25.16 m[a]	$\pm 0.025 m$
Diameter	250.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	100.0 mm	+ 0 mm, - 0.5 mm
Wedge Angle / orientation	2 deg 0 min thick side up	+ 10 min, -0 min
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Reflectivity	> 0.99	
Serial Number	MMT305-1	
Magnet Polarity (see Sec. 6.2.3)	Normal	
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Specified value - Actual value not yet measured.

9.4.2. Risers for MMT2 (2K LHO)

The beam height enters the core optics at a height of +45 mm in the LIGO Global Coordinate system. The plane of the mode cleaner is at -57 mm in the LIGO Global Coordinate system. This difference requires that the beam be directed slightly upwards by the MMT. We step the beam up half between MMT1 and MMT2 and the rest between MMT2 and MMT3. The riser is a solid block 51 mm in height, with provision to clamp the SOS to it and to clamp the riser to the HAM table.

9.5. 4 km IFO MMT at LHO

9.5.1. Optical Component Specifications

Table 38: 4 km MMT1 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Diameter	75.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	25.0 mm	+ 0 mm, - 0.5
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Radius of curvature	6.765 m[a]	$\pm$ 0.005 m
Reflectivity	> 0.99	
Wedge Orientation (see Sec. 6.2.1)	Left	
Serial Number	MMT14k03-1	
Magnet Polarity (see Sec. 6.2.3)	Normal	
Suspension Wire (see Sec. 6.2.4)	Molybdenum	

a. Measured by Dave Ottaway, recorded in email Oct, 2001.

Table 39: 4 km MMT2 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Diameter	75.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	25. 0 mm	+ 0 mm, - 0.5 mm

Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Radius of curvature	3.165 m[a]	± 0.005 m
Reflectivity	> 0.99	
Wedge Orientation (see Sec. 6.2.1)	Left	
Serial Number	MMT24k03-1	
Magnet Polarity (see Sec. 6.2.3)	Normal	
Suspension Wire (see Sec. 6.2.4)	Molybdenum	

a. Measured by Dave Ottaway, recorded in email Oct, 2001.

Table 40: 4 km MMT3 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Diameter	250.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	100.0 mm	+ 0 mm, - 0.5 mm
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Radius of curvature	25.035 m [a]	± 0.025 m
Reflectivity	> 0.99	
Wedge Orientation (see Sec. 6.2.1)	Thick side up	
Serial Number	MMT302-1	
Magnet Polarity (see Sec. 6.2.3)	Normal	
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Measured by Dave Ottaway, recorded in email Oct, 2001.

9.5.2. Risers for MMT2 (4K LHO)

The beam height enters the core optics at a height of +27.8 mm in the LIGO Global Coordinate system The plane of the mode cleaner is at -57 mm in the LIGO Global Coordinate system. This difference requires that the beam be directed slightly upwards by the MMT. We step the beam up half MMT1 and MMT2 and the rest between MMT2 and MMT3. The riser is a solid block 42 mm in height with provision to clamp the SOS to it and to clamp the riser to the HAM table.

9.6. 4 km IFO MMT at LLO

9.6.1. Optical Component Specifications

Table 41: 4 km MMT1 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Front Surface Radius of Curvature	6.76 m[a]	$\pm 0.035m$
Diameter	75.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	25.0 mm	+ 0 mm, - 0.5 mm
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Reflectivity	> 0.99	
Wedge Orientation (see Sec. 6.2.1)		
Serial Number	MMT14k02-1	
Magnet Polarity (see Sec. 6.2.3)		
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Specified value - Actual value not yet measured.

Table 42: 4 km MMT2 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Front Surface Radius of Curvature	3.16 m[a]	$\pm 0.06m$
Diameter	75.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	25. 0 mm	+ 0 mm, - 0.5 mm
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Reflectivity	> 0.99	

Wedge Orientation		
Serial Number	MMT24k01-1	
Magnet Polarity (see Sec. 6.2.3)		
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Specified value - Actual value not yet measured.

Table 43: 4 km MMT3 Specifications

	As-Built	Tolerance
Substrate Material	Fused Silica	
Front Surface Radius of Curvature	25.16 m[a]	$\pm 0.025 m$
Diameter	250.0 mm	+ 1 mm, - 0 mm
Thickness (thick side)	100.0 mm	+ 0 mm, - 0.5 mm
Wedge Angle / orientation	2 deg 0 min thick side up	+ 10 min, -0 min
Transmittance	50 ppm	+ 0 ppm, - 50 ppm
Clear Aperture	60 mm	
Reflectivity	> 0.99	
Serial Number		
Magnet Polarity (see Sec. 6.2.3)		
Suspension Wire (see Sec. 6.2.4)	Steel Music Wire	

a. Specified value - Actual value not yet measured.

9.6.2. Risers for MMT2 (4K LLO)

The beam height enters the core optics at a height of +27.8 mm in the LIGO Global Coordinate system The plane of the mode cleaner is at -57 mm in the LIGO Global Coordinate system. This difference requires that the beam be directed slightly upwards by the MMT. We step the beam up half MMT1 and MMT2 and the rest between MMT2 and MMT3. The riser is a solid block 42 mm in height with provision to clamp the SOS to it and to clamp the riser to the HAM table.

9.7. Alignment Protocol and Tooling

9.7.1. Initial Positioning of the MMT Optics

Initial positioning of the MMT optics was accomplished in a manner similar to MC optics. Initial alignment tolerances are shown below.

Table 44: Initial MMT Alignment Tolerance

Element	*Centering Requirement*	*Position Requirement*
MMT1	3 mm	1 cm
MMT2	3 mm	1 mm
MMT3	3 mm[a]	1 mm

a. ASC requirement for recycling mirror centering

9.7.2. Tooling

Because positioning tolerances are fairly loose, the initial positioning of the MMT within the HAM stacks will be accomplished using the tooling used in the MC optics for MMT1,2. Tooling designs are found in:

1) MMT1 Center Alignment Tool for 4k Machine (LIGO-D980195-00-D)

2) MMT2 Center Alignment Tool for 4k Machine (LIGO-D980196-00-D)

3) MMT1 Center Alignment Tool for 2k Machine (LIGO-D980197-00-D)

4) MMT2 Center Alignment Tool for 2k Machine (LIGO-D980198-00-D)

5) MMT Mounting Alignment Tool (LIGO-D980199-00-D)

6) Assembly Drawing for MMT Alignment Tool (LIGO-D980207)

9.7.3. SOS Installation and Alignment Procedure

Section 6.6 above specifies the MMT SOS installation and alignment.

10 OPTICAL THROUGHPUT

The IOO must deliver 75% of the TEM_{00} light emerging from the PSL to the IFO, including all integrated losses from reflection, transmission, and absorption in the IOO optical components. The following table shows the transmission of the components of the IOO components. Numbers are rounded to 3 digits. For the suspended components we have assumed coatings comparable to those of the core optics, with 30 ppm loss on reflectance. The small optics are assumed to have antireflection coatings that match the Ealing narrowband multilayer coatings (0.1%). The largest individual loss comes from the large Faraday isolator, where the polarizing components contribute to a total loss of 8%.

Table 45: Optical efficiency of IOO system

Item	*Designed Transmittance*	*4k LHO As-built*	*2k LHO As-built*	*4k LLO As-built*
RF modulation core optics	0.985			
RF for mode cleaner	0.990			
3 mode matching lenses	0.994			
HAM1 window	0.998			
3 beam steering mirrors	0.999			
Mode cleaner	0.950	0.64[a]	0.86[b]	0.90[c]
Faraday isolator	0.920	0.87[d]	0.91[e]	
Mode matching telescope (4 mirrors)	0.996	0.93[f]	0.82[g]	

a. See LHO Detector elog Dec. 31, 2002 by P. Fritschel.
b. See LHO Detector elog May 2, 2003 by V. Parameshwariah, D. Sigg.
c. See LLO Detector elog, Dec. 13, 2000 by D. Reitze.
d. See T030134, LIGO Notes on Faraday Isolator Measurements.
e. See d above.
f. See a above.
g. See b above.

11 DIAGNOSTICS

11.1. PSL/IOO Table

11.1.1. RF Amplitude Modulation Monitor

RF amplitude modulation of the laser beam after passing the EOMs is monitored off line by a New Focus model 1811 photodiode. The dc signal from the photodiode will also be monitored. The ratio of the RF signal at the three modulation frequencies will be compared with dc signal to calculate the amount of residual RFAM.

11.1.2. RF Sideband Monitor

RF sidebands generated by the EOMs will be monitored off line with either a Burleigh CF(T)-500S-NIRoptical spectrum analyzer or similar model.. The resolution of the optical spectrum analyzer is about 1.5 MHz. To distinguish the smallest sidebands from the tail of the carrier, the temporal signal will be recorded by a digital oscilloscope and read to a computer. A fitting procedure will be used to calculate the intensities of the sidebands.

An optical spectrum analyzer will be located on the PSL table for monitoring sidebands before the mode cleaner.

An optical spectrum analyzer will be located on the IOT table for monitoring sidebands after the mode cleaner.

11.2. Mode Cleaner Diagnostics

Taken care of by ISC. Refer to LIGO-T970218-01-D

11.3. Mode Matching Wavefront Sensing

Not yet implemented at the sites.

12 HIGH POWER COMPONENTS

Table 46 summarizes the results of the measurement and compare them with the requirement.

Table 46: Summary of measurement

item	*requirement*	*measurement*
Dynamic displacement by stray B-field of Faraday rotator (FR)	$4x10^{-9}$ m/Hz$^{0.5}$ (@1 Hz) $1x10^{-12}$ m/Hz$^{0.5}$ (@10 Hz) $3x10^{-23}$ m/Hz$^{0.5}$ (@100 Hz)	$1x10^{-12}$ m/Hz$^{0.5}$ (@1 Hz) $5x10^{-17}$ m/Hz$^{0.5}$ (@10 Hz) $6x10^{-28}$ m/Hz$^{0.5}$ (@100 Hz)
Vacuum contamination of FR (hydrocarbon pressure)	5 x 10^{-11} torr	9.4 x 10^{-12} torr
Power loss by FR thermal lensing	5%	3%
FR polarization	100:1	170:1

item	*requirement*	*measurement*
FR isolation	-35 dB	<-36 dB
Electro-Optical Modulator (EOM) residual intensity modulation	1×10^{-3}	$<2.5 \times 10^{-6}$
Alignment tolerance	4.3 deg	0.02 deg

12.1. Alignment Tolerance

The alignment between the angles of the EOM's axis and the incident polarization/the polarizer must be small enough to make the residual intensity modulation caused by RFAM be lower than the required value of 1×10^{-3}. Table 47 shows the corresponding alignment tolerance.

Table 47: Required alignment tolerance

required RFAM (in intensity modulation)	*alignment tolerance*	*best alignment achieved*
1×10^{-3}	4.3 deg	0.02 deg

12.2. EO Modulator Selection (Type, Manufacturer, etc.)

Table 48 shows the specifications of the selected EOM.

Table 48: EOM specifications

Manufacturer	*New focus, Inc.*
Model #	4003
Wavelength	1.0 - 1.6 µm
Type	Resonant Phase Modulator
Operating Frequency	0.01 to 190 MHz
Modulation depth	0.1 - 0.3 rad/V @ 1 µm
Max Vπ	10 - 31 V @ 1 µm
Material	$LiNbO_3$
Max Optical intensity	1 W/mm^2 (1.3 1 µm)
Aperture	2 mm

Table 48: EOM specifications

RF Bandwidth	2 - 4% freq.
Impedance	50 ohm
Max RF Power	1 W