LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	LIGO-T980104-01 -	D	11/18/98

COS Final Design

Michael Smith, Ara Badalian, Craig Conley, Paul Kabot,
Jonathan Kern, Ken Mailand, Angel Rosa, Dennis Rose

Distribution of this draft:

xyz

This is an internal working note
of the LIGO Project..

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

1 COS FDR OVERVIEW

This document presents the Core Optics Support subsystem final design. It summarizes the requirements and gives a detailed description of each of the COS elements.

- PO Telescope
- ETM Telescope
- Beam Dumps
- Baffles
- Other COS Elements
  - Faraday Isolator
  - Pickoff Mirror
  - Steering Mirrors
  - Vacuum Window

1.1. Relevant Documents

Core Optics Support Design Requirements Document, LIGO-T970071-02-D
Core Optics Support Conceptual Design, LIGO-T970072-00-D
Core Optics Support Preliminary Design, LIGO-T970071-02-D
Bafling Requirements for the 4K and 2K IFO, LIGO-T980027-00-D
Up-Conversion of Scattered Light Phase Noise from Large Amplitude Motions, LIGO-T980101-00
ETM PO Beam Optical Relay System, LIGO-T980071-00-D
COS Beam-dump & Stray Light Baffle Revised Requirements and Concepts, LIGO-T980103-00
Determination of Deflection Requirements for BSC Support Beam Bellows, HYTEC-TN-LIGO-08a.
ETM PO Beam Optical Relay System, LIGO-T980071-00-D
PO Beam Waist Size and Location on the ISC Table, LIGO-T980054-02-D

1.2. Definitions and Acronyms

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

- beam-dump, a light trap used to absorb unwanted ghost beams
- vh - Vacuum housing
- SEI - Seismic Isolation subsystem
- SUS - Suspension subsystem
- ppm - parts per million
- ISC- Interferometer Sensing and Control
- LSC - Length Sensing and Control
- COC - Core Optics Components
- ASC - Alignment Sensing and Control
- ISC - Interferometer Sensing and Control
- IFO - LIGO interferometer
- HAM - Horizontal Access Module
- BSC - Beam Splitter Chamber
- BRDF - Bidirectional Reflectance Distribution Function
- TBD - To Be Determined
- APS - anti-symmetric port signal
- SPS - symmetric port signal
- rms - root-mean-square
- p-v, peak to valley

1.3. Layout Of COS Elements In The Washington Interferometer

A plan view layout of the detector assembly is shown in the following figures, indicating the physical relationship of the COS subsystem components to the rest of the detector system. The vertex station in shown in figure 1. The mid station is shown in figure 2. And the end station is shown in figure 3.

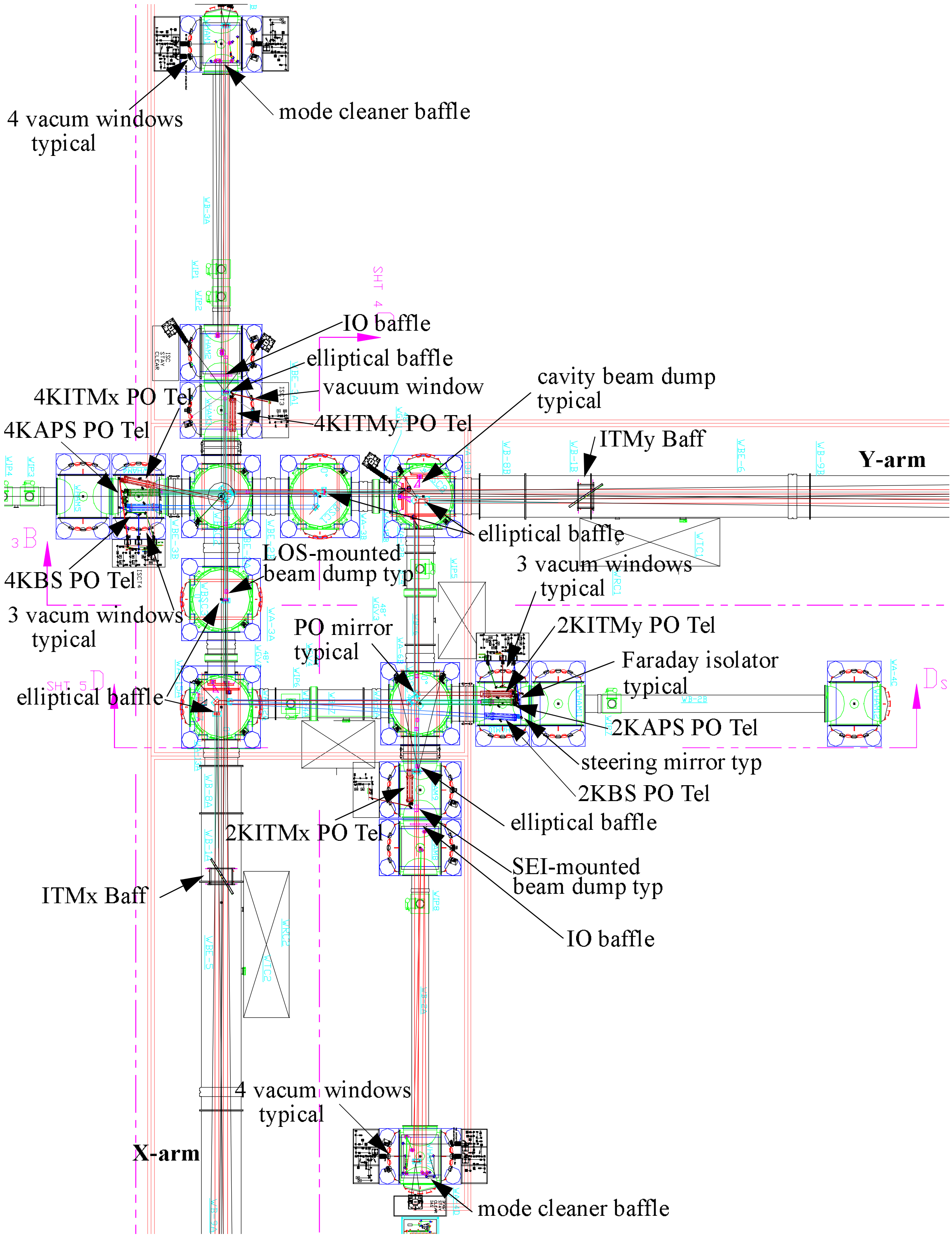

Figure 1: Core Optics Support Subsystem Elements, Vertex Station

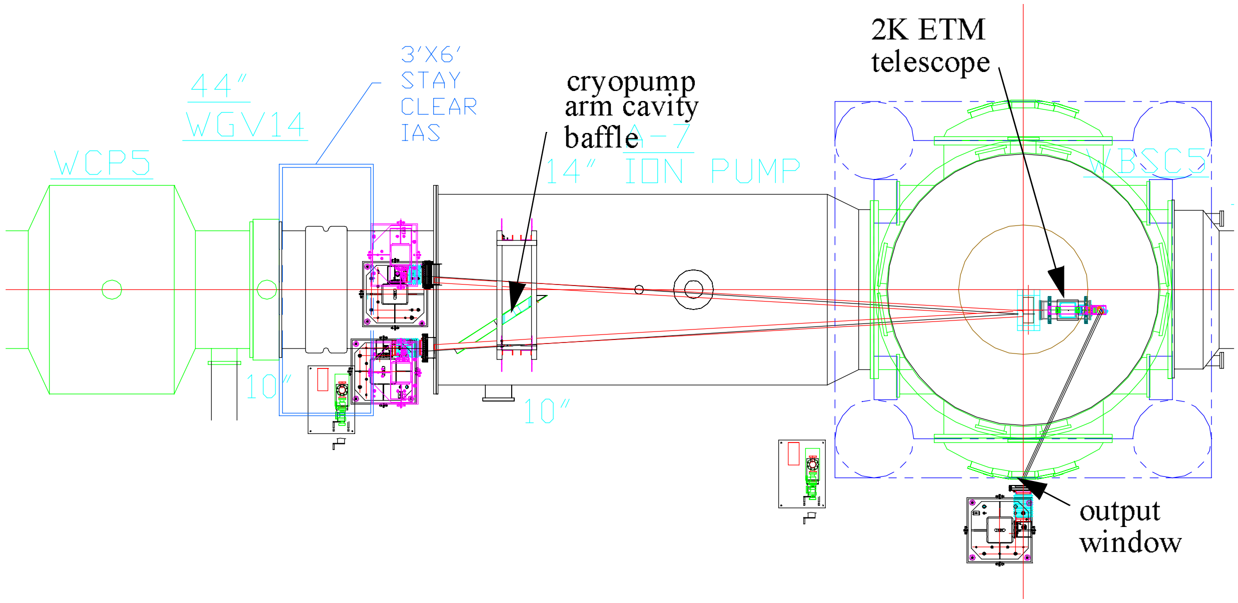

Figure 2: Core Optics Support Subsystem Elements, Mid Station

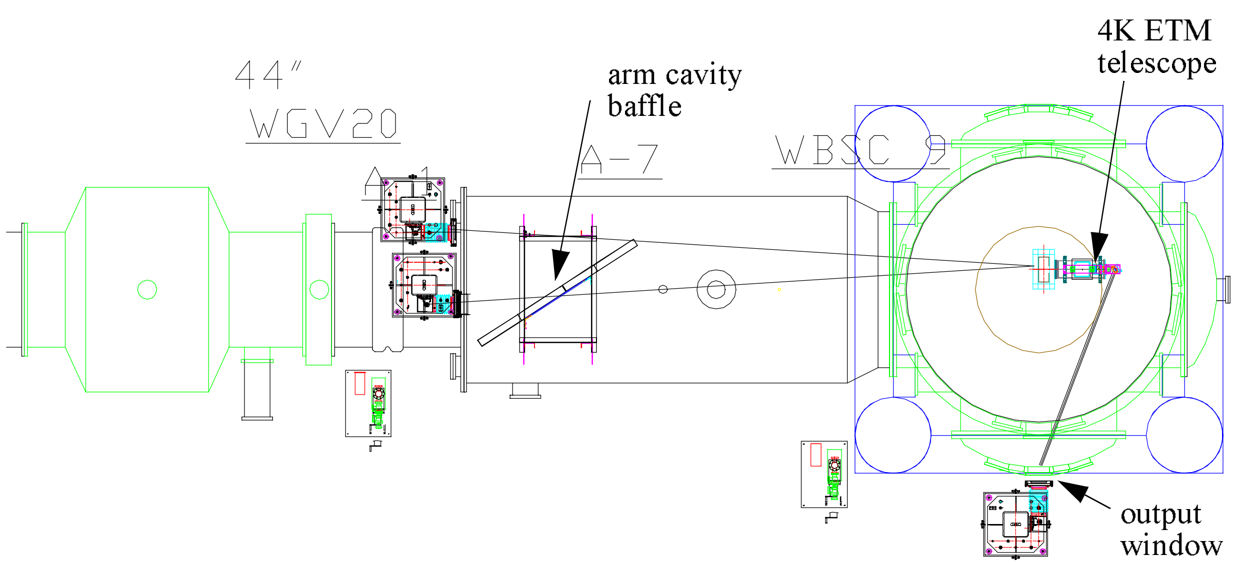

Figure 3: Core Optics Support Subsystem Elements, End Station

1.4. Ghost Beam Designation

The ghost beams created by the wedge surfaces of the RM, BS, ITM, and ETM are numbered according to the schematic drawing in figures 4 and 5.

The first surface reflection from the RM, ITTM, and ETM COC is designated GBAR1. The main beam is designated 2. The higher order ghost beams leaving the AR surface are designated GBAR3, GBAR4, etc. The ghost beams leaving the HR surface are designated GBHR3, GBHR4, etc.

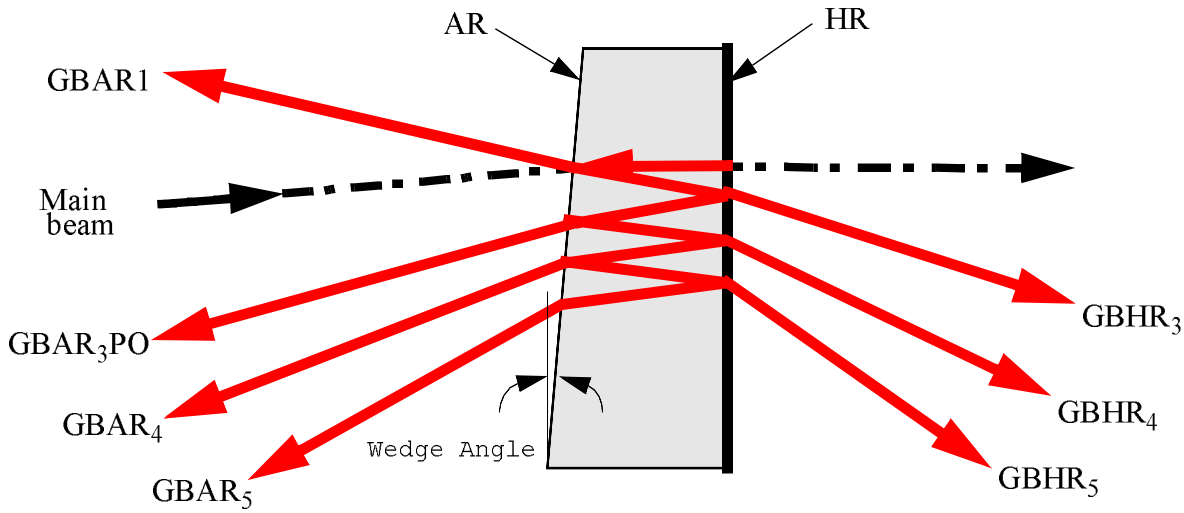

Figure 4: Optical Beam Designation: RM, ITM, ETM

.

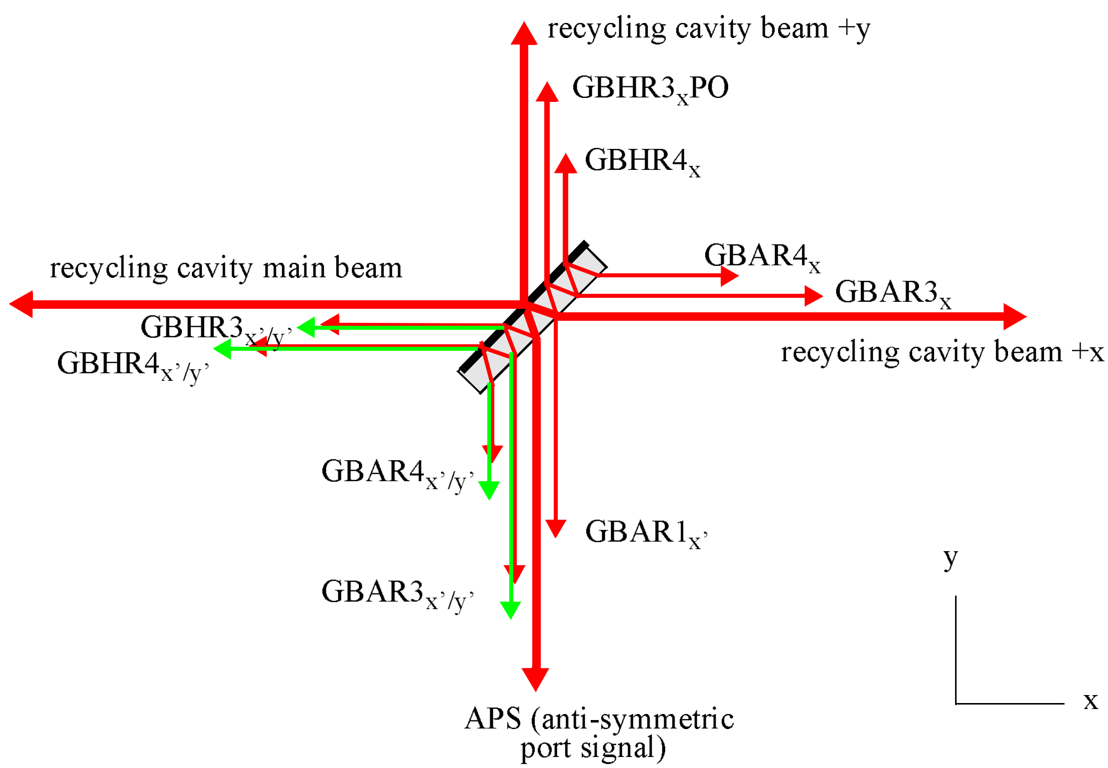

Figure 5: Optical Beam Designation: beam splitter

The BS has four sets of ghost beams, as shown in figure 5. Ghost beams which originate in the +x direction are designated sub x; beams which originate in the -x direction are designated sub x'; beams which originated from the -y direction are designated sub y'.

1.5. Scattered Light in the Interferometer

1.5.1. Light Scattering Requirements

- The LIGO requirement for light power scattered back into the IFO from moving surfaces is that the resulting phase noise shall not exceed 1/10 the initial LIGO sensitivity as given in the LIGO Science Requirements Document: LIGO-E950018-02-E.
- This noise requirement was translated into a maximum total scattered power requirement for scattering from seismic floor-mounted surfaces, as described in COS DRD LIGO-T970071-01-D.
- The total scattered power was *optimally budgeted* within the various scattering paths so that the rms sum of the individual paths equalled the total scattered power requirement.
- The scattered power budget became the implied requirement for maximum scattered light from each scattering path.

1.5.2. COS Scattered Light Control Design Approach

The objective of the COS scattered light control design approach was to minimize the required number of baffles and beam-dumps inside the vacuum enclosure, to keep the baffles and beam-dumps off of the SEI platforms whenever possible, to minimize the light scattering budged used by COS, and to specify the maximum allowed power scattered from each PO beam by surfaces outside the vacuum enclosure which would meet the LIGO scattered light phase noise requirements.

The criteria for deciding which ghost beams should be dumped and the placement of baffles in the IFO beam path was based on the likelihood of glint reflections from the walls of the vacuum chamber causing excessive phase noise.

The maximum allowed power scattered from each PO beam *by external surfaces* places an implied requirement on the BRDF of the external scattering surfaces; which depends upon the diameter of the beam, the power spectrum of the moving surface, and the particular PO beam path.

The COS design approach is summarized in the following.

- All GBAR1, and unused GB3 ghost beams will be caught by beam-dumps mounted to the walls of the vacuum housing.
- GB4 ghost beams with $P_{incident} < 50\times10^{-6}$ watts will *not* be dumped.
- ITM GB4 ghost beams will be dumped.
- the glint from undumped ghost beams hitting the vacuum chamber will *not exceed* the scattered light requirement.
- PO mirrors, PO telescopes, and all accessory PO beam optics will be rigidly mounted on SEI platforms.

- Faraday isolator in APS beam and ND filter in ETM PO beam are *required* to balance the scattered light budget
- Recommended $BRDF < 8\times10^{-4}$ sr^{-1} for all seismic floor-mounted optical surfaces in the demagnified PO beam train
- Stray light baffle to block IOO mode-cleaner scattered light from entering the recycling cavity
- Stray light baffle to block small-angle scattered light from ITM and ETM exiting the beam tube.
- Cryopump baffle to hide internal reflecting surfaces of cryopump at ends of beam tubes.

1.5.3. Estimate of Light Power Scattered into the IFO

A summary of the estimated scattered light power into the 4K IFO from the first two orders of ghost beams is shown in COS Preliminary Design LIGO-T980010.

2 TELESCOPES

2.1. Telescope Requirements

Table 1: Telescope Requirements

Property	*PO Telescope*	*ETM Telescope*
Configuration	off-axis parabolic, afocal	on-axis refractive, afocal
Clear input aperture, mm	160 mm	160 mm
Field of view	$\Delta\theta = \pm5\times10^{-4}$ rad	$\Delta\theta = \pm2\times10^{-4}$ rad
Beam reduction	8X	8X
Wave front aberration	< 0.25 waves p-v @ 1064nm	not applicable
Optical transmissivity	>99.8% @ 1064 nm	>90% @ 1064 nm

2.2. Pick-off Telescope Final Design

2.2.1. Primary Mirror

2.2.1.1 Front Surface

Radius of curvature	-3048 mm +/- 30
Conic constant	-1.000 +/- 0.002
Parabolic tilt, reference to back surface	+/- 0.03 deg
Clear aperture	200.7 mm

Edge displacement	108.00 +/- 0.12 mm
Diameter	203.2 +0.0, -0.1 mm
minimum edge thickness	43 mm +/- 0.5 mm
Surface quality	<l/8 wave peak to valley@ 633 nm over clear
Surface finish	60/40
Surface roughness	<100 Ang

2.2.1.2 Back Surface

Surface quality	fine ground, >300 grit

2.2.2. Secondary Mirror

2.2.2.1 Front Surface

Radius of curvature	-381 mm +/- 4
Conic constant	-1.000 +/- 0.02
Tilt tolerance, reference to back surface	+/- 0.05 deg
Clear aperture	32.0 mm
Off-axis displacement	26.20 +/- 0.01 mm
Diameter	34.0 +0.0, -0.1 mm
Minimum edge thickness	20.0 +/-0.1 mm
Surface quality	<l/8 wave peak to valley@ 633 nm over clear
Surface finish	60/40
Surface roughness	<100 Ang

2.2.2.2 Back Surface

Surface quality	fine ground, >300 grit

2.2.3. Mirror Coating

Front surface only	
Wavelength	1064 nm
Polarization	s
Incidence angle	4 deg
Reflectivity	>99.9%
Durability	per MIL-C-675C

2.2.4. Mechanical Characteristics

2.2.4.1 PO Telescope Mechanical Assemblies

The PO Telescope consists of the following mechanical assemblies:

1)primary mirror mount,
2)secondary mirror mount,
3)telescope housing,
4)optical reference plate,
5)output flange,

6)front support,
7)tilt yoke,
8)height and tilt alignment fixtures,
9)input aperture alignment target, and
10)primary mirror aperture alignment target.

2.2.4.2 Telescope Configuration

The PO Telescope is used in two orientations,

1) **down**, primary mirror on the bottom, and
2) **up**, primary mirror on the top; in conjunction with two fixed heights and two adjustable heights; for a total of eight unique configurations. The optical centerline height and the pitch angle are determined by the lengths and the attachment points of the front support and the rear tilt yoke support. The yaw angle is determined by translating the front support parallel to the optical table with respect to the rear tilt yoke support. The front of the telescope is the end where the secondary mirror is mounted, and the rear of the telescope is the end where the primary mirror is mounted.

2.2.4.3 Telescope Supports

All eight configurations and optical centerline heights shall be set with only three universal supports:

1) fixed length front support,
2) fixed length rear support, and
3) tilt yoke.

2.2.4.4 Height and Tilt Adjustment Range

As a minimum; the height, height range, and tilt angle adjustments shall cover the range of values shown in Table 2 on page 10. The heights are measured from the surface of the optical table.

Additional mounting holes shall be provided on the sides of the telescope housing so that the front telescope supports can be moved to eliminate mechanical interferences with adjacent telescopes.

2.2.4.5 Focussing and Alignment of the Output Beam

The secondary mirror mount will provide focussing and alignment adjustments for the output beam.

2.2.4.6 Positioning and Fastening Requirements

The telescope assembly shall be positioned anywhere and securely fastened to the surface of the HAM SEI optical platform by means of the array of 1/4-20 tapped holes in a 2in X 2in pattern on the platform using clamps, as shown in figures 10, 11, 12 , and 13.

2.2.4.7 Height and Tilt Alignment Fixtures

2.2.4.7.1 Tilt Yoke Assembly, Differential Screw Mover

The differential screw mover, as shown in figure 7. shall translate the tilt yoke assembly transverse to the optical axis within the required positioning range, with a minimum positioning repeatability of 0.01 inch.

PO Telescope		Relative dim, in			
		nominal height gimbal, in	nominal height front support, in	height range, in	tilt angle, deg
2K	ITMx	15.63	15.69	0.0	-2.1
2K	ITMy	15.63	15.69	0.0	-1.9
2K	APS	10.43	10.46	0.5	-1.1
2K	BS	15.63	15.63	0.0	-0.1
4K	ITMy	15.63	15.63	0.0	0.0
4K	ITMx	15.63	15.63	0.0	0.0
4K	APS	8.78	8.81	0.5	-1.1
4K	BS	15.63	15.65	0.0	-0.6
4K - La	ITMy	15.63	15.63	0.0	0.0
4K - La	ITMx	15.63	15.63	0.0	0.0
4K - La	APS	8.78	8.81	0.5	-1.1
4K - La	BS	15.63	15.65	0.0	-0.6

Table 2: Height, height range, and tilt angle for the PO Telescopes

2.2.4.7.2 Pitch Adjustment Mechanism

A removable pitch adjustment mechanism will be positioned under the PO Telescope approximately at the center of gravity to provide a fine pitch tilt adjustment. The pitch adjustment mechanism shall provide all the required pitch angles, within a minimum angle repeatability of 5×10^{-5} rad. The pitch adjustment mechanism shall allow the PO Telescope to translate in the plane of the optical table, while maintaining the minimum tilt repeatability.

2.2.4.7.3 Yaw Adjustment Mechanism

A removable yaw adjustment mechanism will be positioned at the front end of the PO Telescope to provide a fine yaw tilt adjustment. The yaw adjustment mechanism shall provide all the required yaw angles, within a minimum angle repeatability of 5×10^{-5} rad.

2.2.4.8 Input Aperture Alignment Target

A removable alignment target shall be placed at the entrance aperture of the PO Telescope within $\pm20\times10^{-3}$ in of the optical centerline.

2.2.4.9 Primary Mirror Aperture Alignment Target

A removable alignment target shall be placed in front of the primary mirror of the PO Telescope within $\pm 20\times10^{-3}$ in of the optical centerline.

2.2.4.10 Optical Reference Surface

The optical reference surface shall be mounted perpendicular to the sides of the housing to within 4×10^{-4} rad.

2.2.4.11 Output Flange

An alignment telescope (not part of this specification) will be centered co-linear with the output optical centerline by means of the output flange which mounts to the optical reference surface. An adjustment means will be provided so that the output flange shall be positioned to within $\pm 2.5\times10^{-3}$ in of the optical centerline. The inside bore of the output flange shall be perpendicular to the optical reference surface to within 4×10^{-4} rad.

2.2.4.12 Mechanical Tolerances

2.2.4.12.1 Primary Mirror Mount

The flat mounting surface of the primary mirror shall be fixed mounted parallel to the optical reference surface within 0.02 deg.

The center of the primary mirror shall be fixed mounted within $\pm 20\times10^{-3}$ in of the nominal primary mirror optical centerline.

2.2.4.12.2 Secondary Mirror Mount

The flat mounting surface of the secondary mirror shall be adjusted parallel to the optical reference surface within 0.05 deg.

The transverse position of the secondary mirror shall be adjusted so that the output optical axis is perpendicular to the optical reference surface within 0.05 deg.

The lateral position of the secondary mirror shall be adjusted to focus the cross hairs of the alignment telescope reticle.

2.2.4.13 Mechanical Vibration Characteristics

The telescope, and its associated mounting structure shall have no internal mechanical resonances <100Hz.

2.2.4.14 Size and Weight

- Maximum size envelope, see figure 7.
- Maximum weight of telescope without supports <55 lb

2.2.5. Optical Schematic Layout, PO Telescope

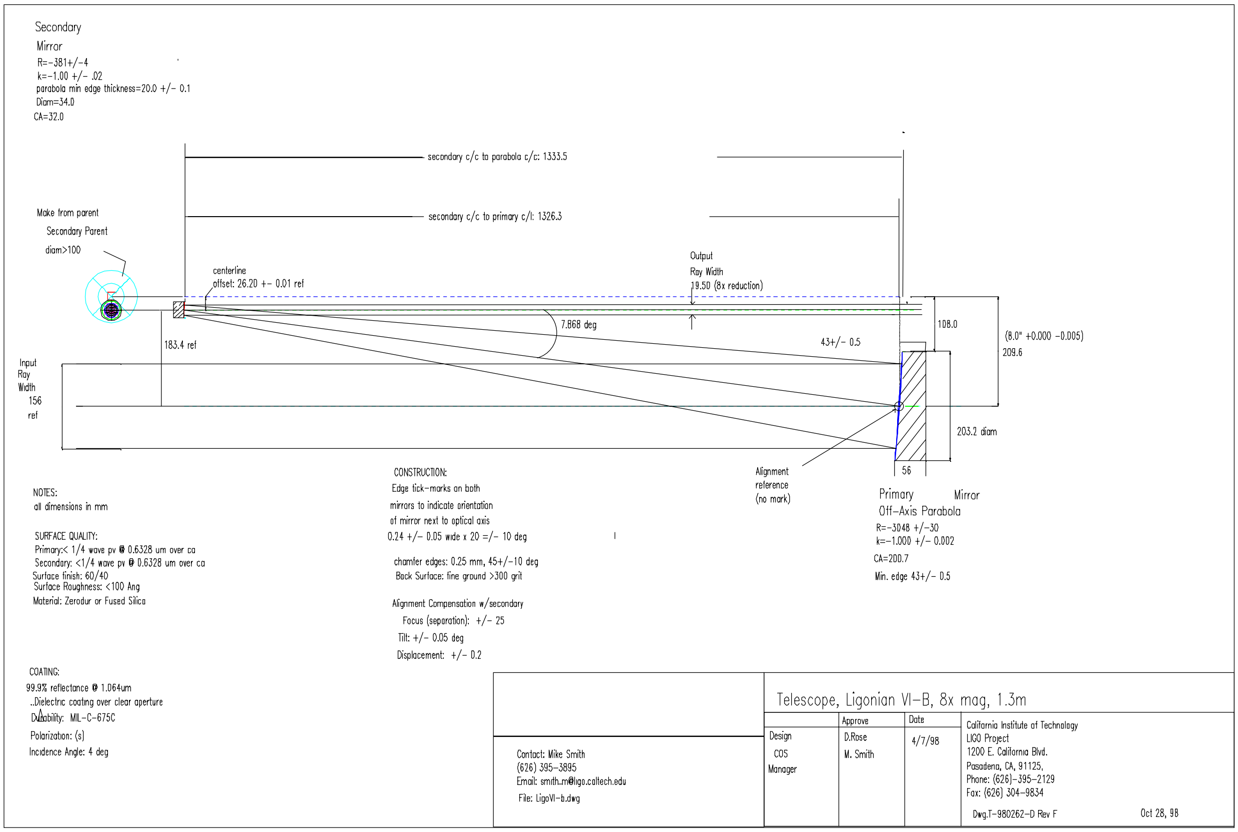

Figure 6: Optical schematic layout for PO telescope

2.2.6. Mechanical Layout of PO Telescope

The PO telescope is shown in figure 7 with the primary mirror up for the ITM, and BS configurations. In the APS configuration the telescope is flipped over so the primary mirror is down.

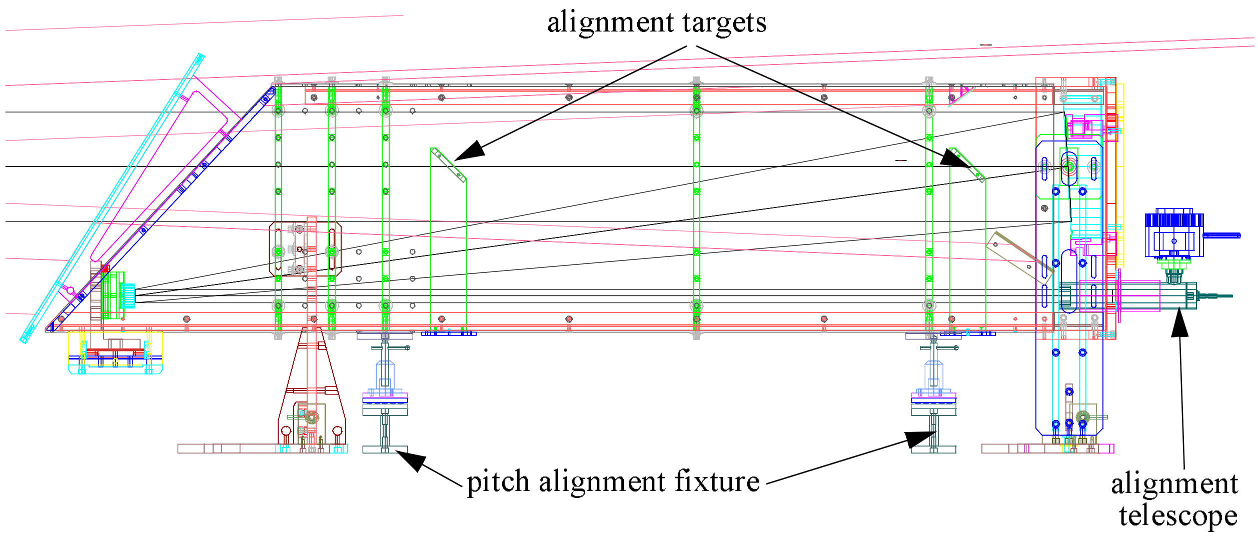

Figure 7: PO Telescope, side view

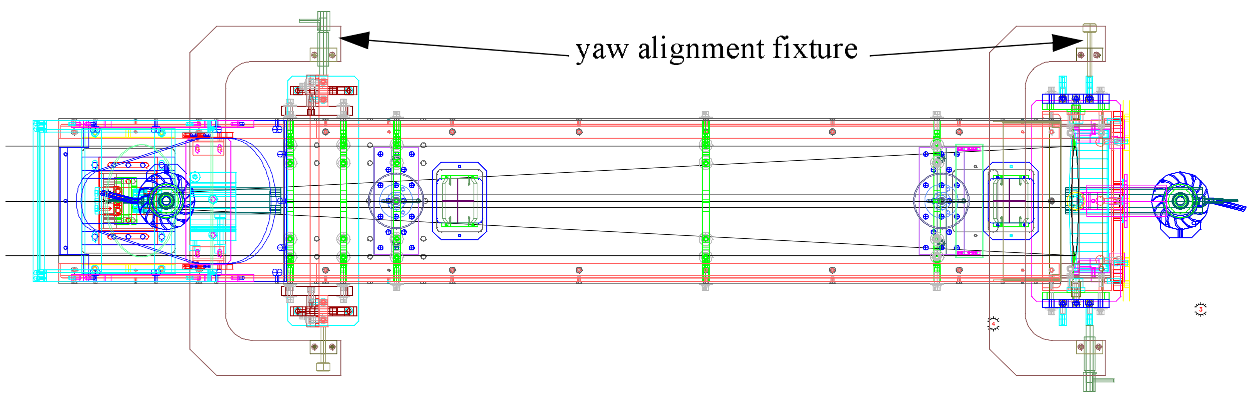

Figure 8: PO Telescope, top view

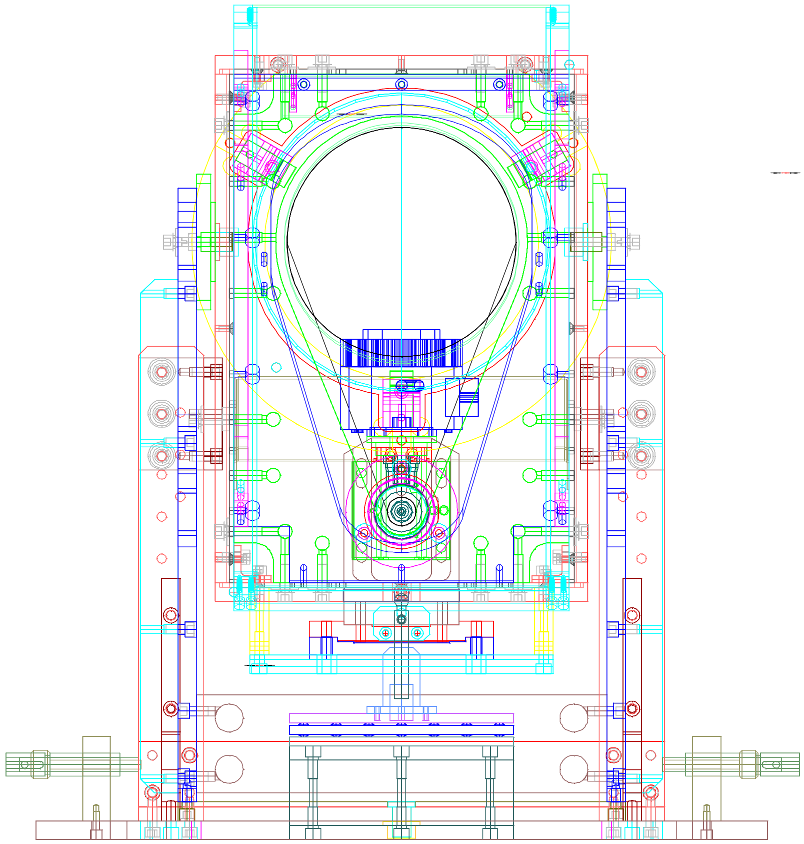

Figure 9: PO Telescope, end view

2.2.7. Pick Off Beam Optical Train Layout

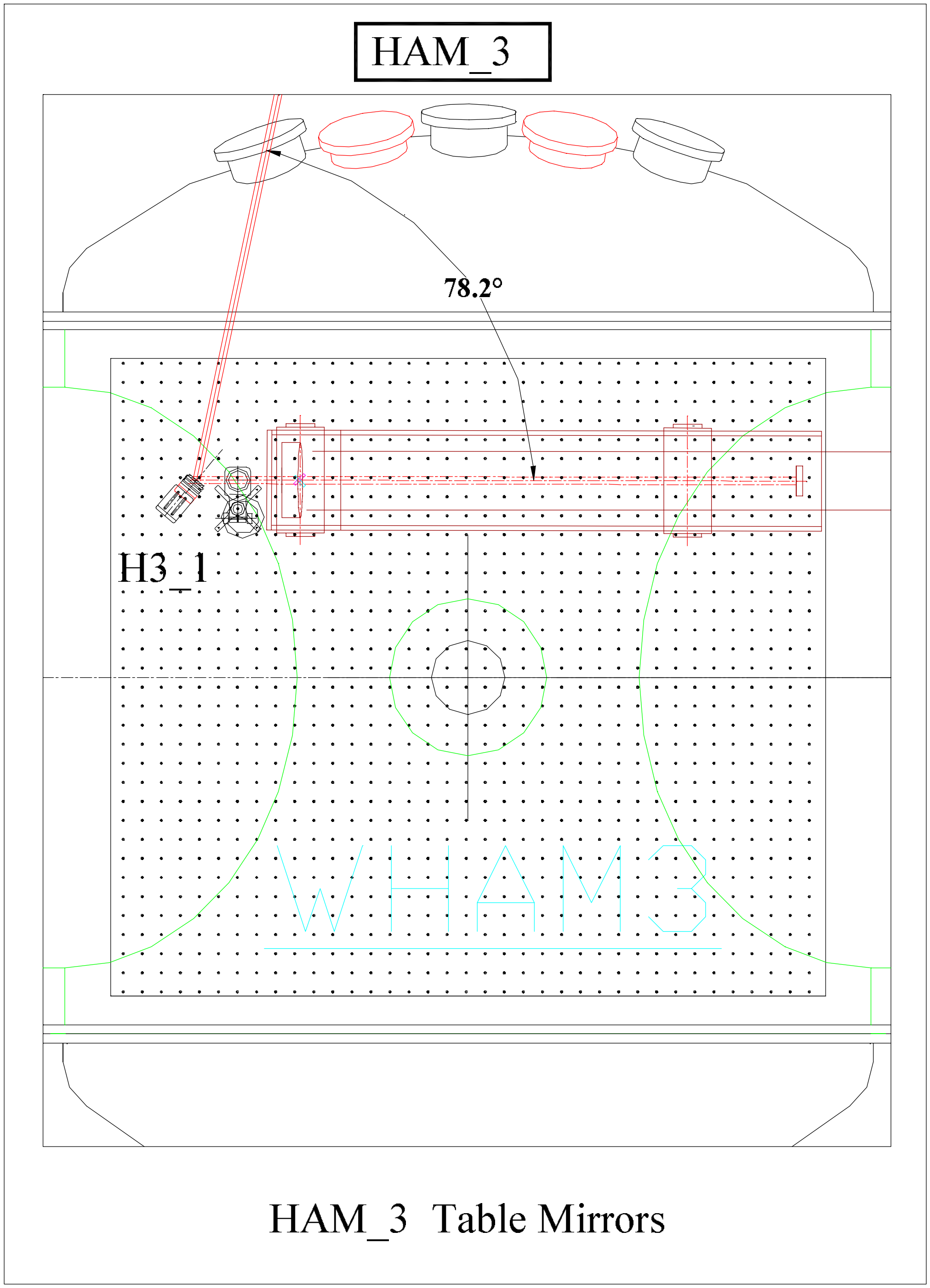

Figure 10: PO Telescope 4K ITMy, orientation

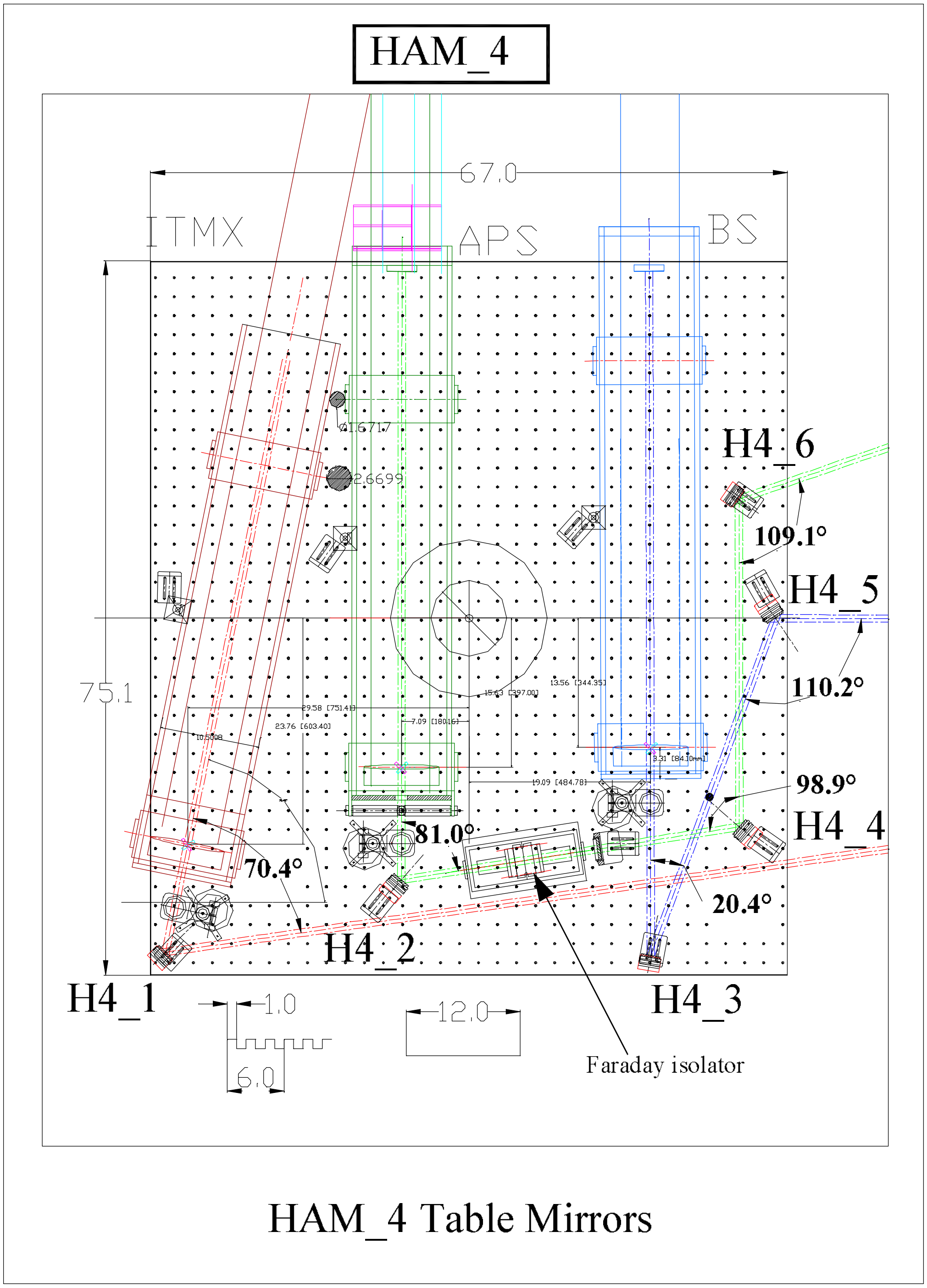

Figure 11: PO Telescopes 4K ITMx, 4K BS, 4K APS orientation

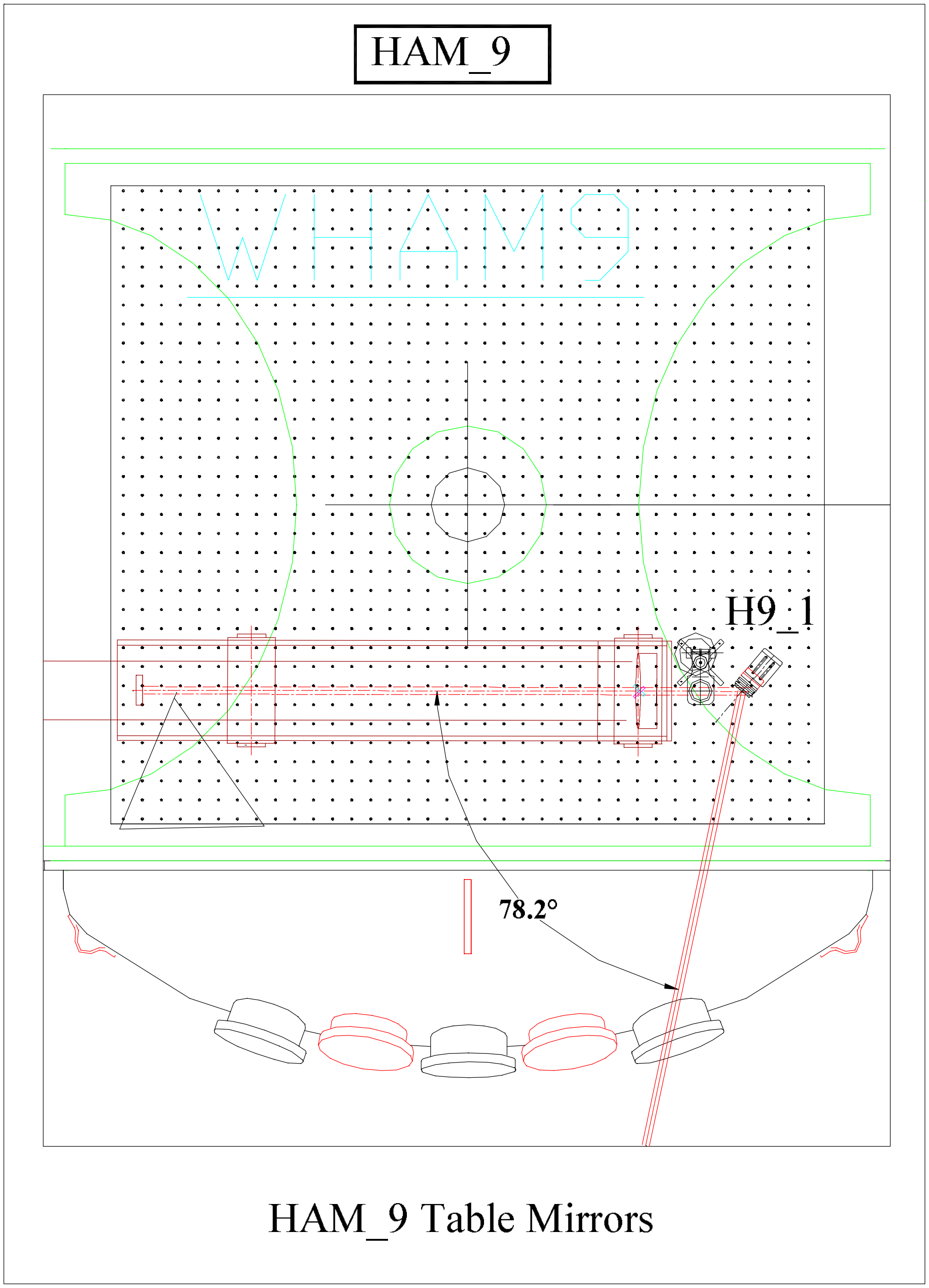

Figure 12: PO Telescope 2K ITMx, orientation

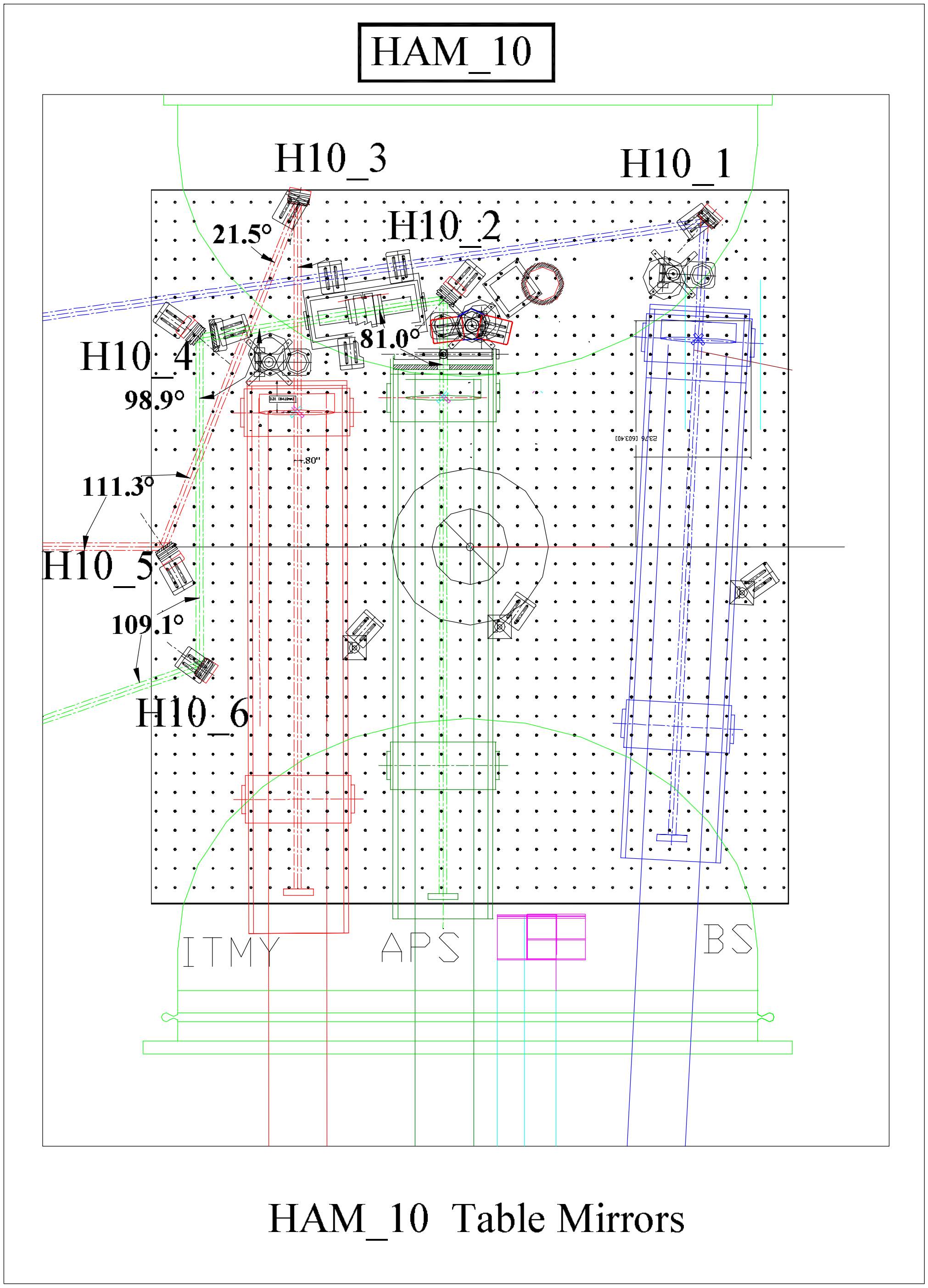

Figure 13: PO Telescopes 2K ITMy, 2K BS, 2K APS orientation

2.3. ETM Telescope

2.3.1. Optical Characteristics

2.3.1.1 Objective Lens

material	BK7
process	conventional polish
surface finish	40-20
surface roughness	<100 Ang.
anti-reflection coating	>99.5 % transmissivity per surface
edge	fine ground
edge bevel	45 degj
operating wavelength	1064 nm
index of refraction tolerance	+/- 0.001
radius 1	368.30
radius 2	-4494.2
wavefront aberration- power	<0.5 waves
wavefront aberration- irregularity	<0.12 waves
clear aperture diameter	170.0
edge diameter	176.0, -0.02 +0.00
central thickness	24.0, +/-0.5
wedge	<0.0340 TIR

2.3.1.2 Eyepiece 1 Lens

material	BK7
process	conventional polish
surface finish	40-20
surface roughness	<100 Ang.
anti-reflection coating	>99.5 % transmissivity per surface
edge	fine ground
edge bevel	45 deg
operating wavelength	1064 nm
index of refraction tolerance	+/- 0.001
radius 1	78.88
radius 2	165.33
wavefront aberration- power	<0.5 waves
wavefront aberration- irregularity	<0.12 waves
clear aperture diameter	70.0
edge diameter	74.00, -0.02 +0.00
central thickness	10.00, +/-0.50
wedge	<0.070 TIR

2.3.1.3 Eyepiece 2 Lens

material	SF6
process	conventional polish
surface finish	40-20
surface roughness	<100 Ang.
anti-reflection coating	>99.5 % transmissivity per surface
edge	fine ground
edge bevel	45 deg
operating wavelength	1064 nm
index of refraction tolerance	+/- 0.001
radius 1	-64.39
radius 2	70.49
wavefront aberration- power	<0.5 waves
wavefront aberration- irregularity	<0.12 waves
clear aperture diameter	40.0
edge diameter	44.0, -0.02 +0.00
central thickness	10.0 +/-0.5
wedge	<0.040 TIR

2.3.2. Mechanical Characteristics

The optical center line of the ETM telescope will be suspended by a vertical support column below an optical table, as shown in figure 15. The ETM telescope shall be attached to the support column so as to enable 4 degrees of freedom. That is, the optical barrel shall be moveable transverse to the optical axis in the horizontal and vertical planes, and shall tilt in pitch and yaw to the following limits:

- V-plane:+/- .5 inches total, +-.020 inches fine adjustment
- H-plane:+/- .5 inches total, +-.020 inches fine adjustment
- Yaw axis:+/- 2 degrees total, +-1minute fine adjustment
- Pitch axis:+0.0/-3 degrees total, +-1minute fine adjustment
- Position of optical axis below optical table: 600mm

A bracket is provided at the output of the ETM telescope for attaching a steering mirror mount to be oriented at approximately 45 degrees, as shown in figure 16.

2.3.2.1 Mechanical Tolerances

The assembly shall be designed to maintain the optical element's mounting tolerances as follows

- Mounting ID, Lens 1= 176.05mm +0.05 / -0.00mm
- Mounting ID, Lens 2= 74.05mm +0.05 / -0.00mm
- Mounting ID, Lens 3= 44.05mm +0.05 / -0.00mm
- Tilt = 0.056 degree max
- Mechanical decenter = 0.2mm

2.3.2.2 Focus compensation

- focus adjustment, separation between elements L1 and L2 = 369.476mm, +/-12mm

- fixed spacer tube, separation between elements L2 and L3 = 81.523mm

2.3.2.3 Mechanical Vibration Characteristics

The telescope, and its associated mounting structure shall have no internal mechanical resonances <100Hz.

2.3.2.4 Size and Weight

- Maximum size envelope - 30l x 10w x30h inches
- Maximum weight of telescope, and its associated mounting structure- <45 pounds

2.3.3. Optical Schematic Layout, ETM Telescope

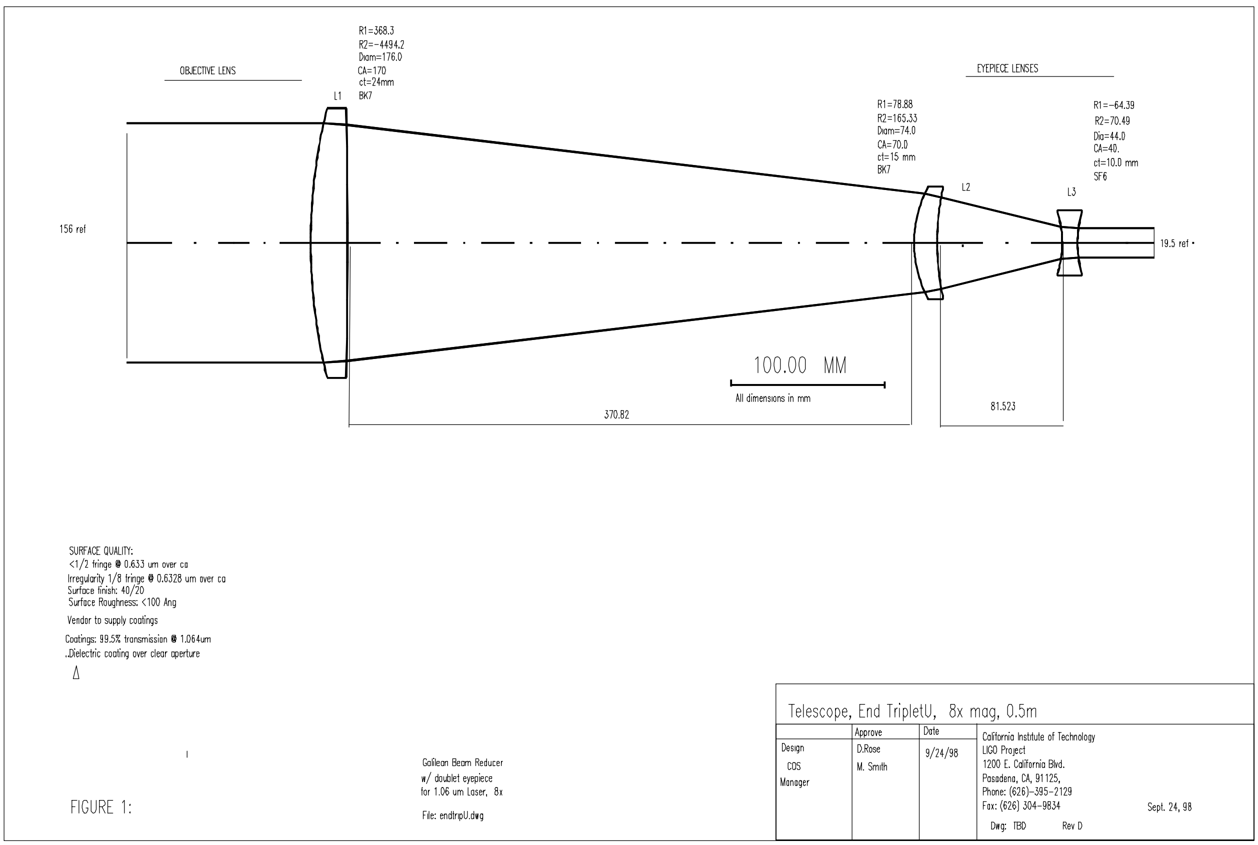

Figure 14: ETM Telescope, optical layout

2.3.4. Mechanical Layout

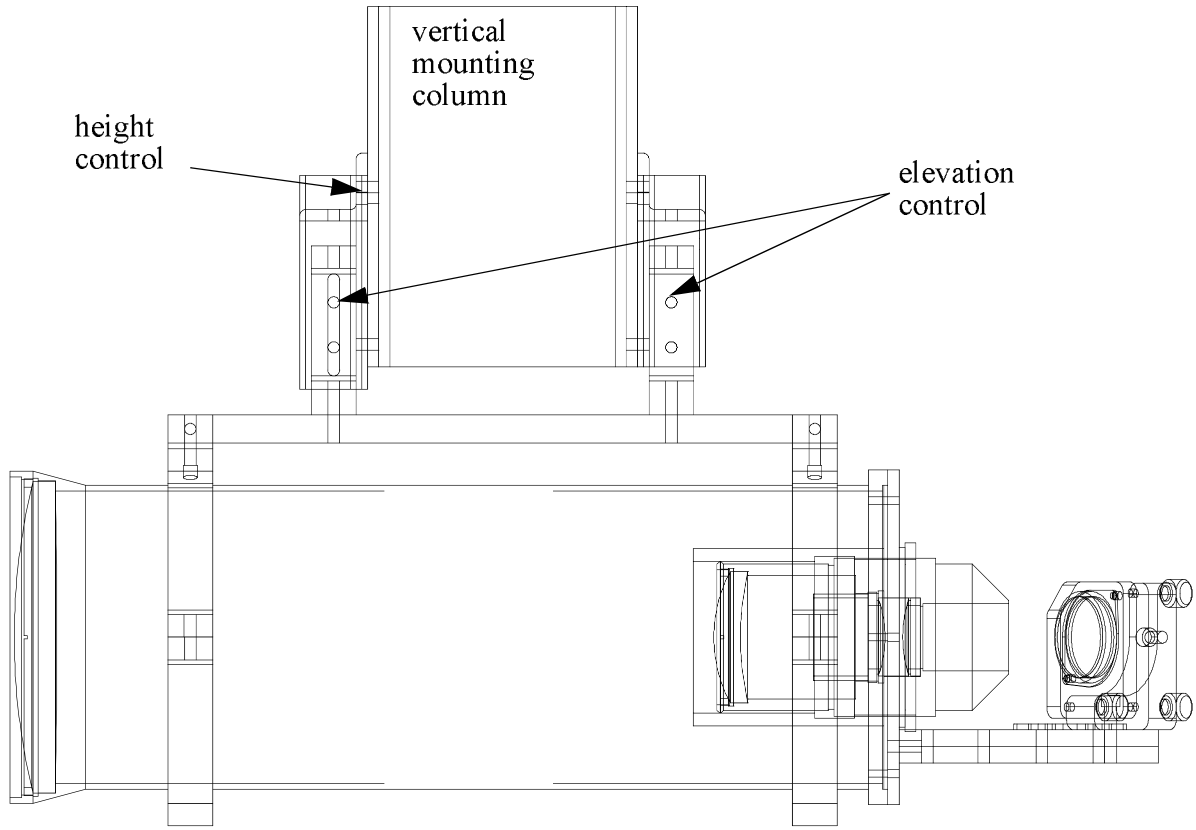

Figure 15: ETM Telescope, side view mechanical layout

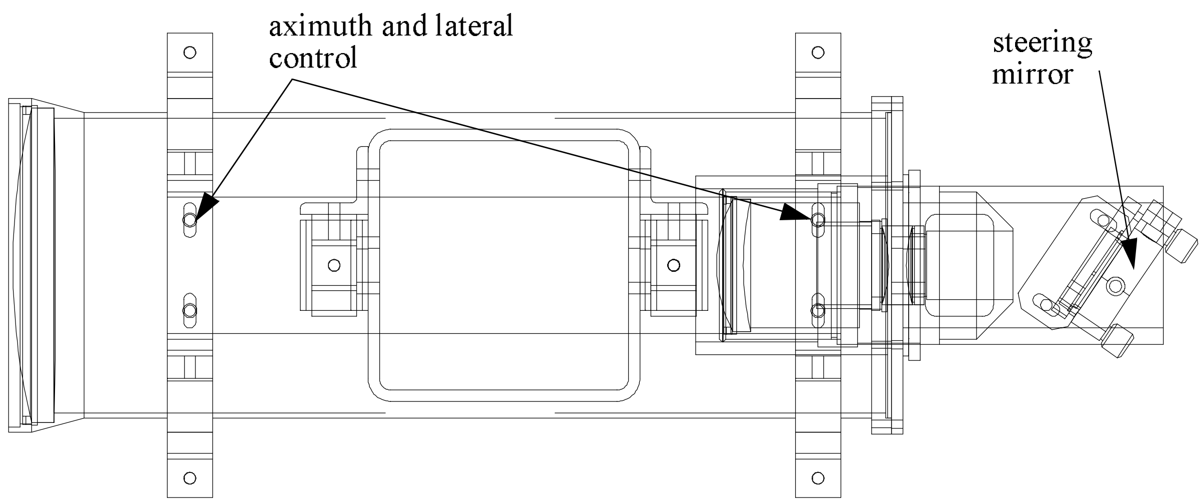

Figure 16: ETM Telescope, top view mechanical layout

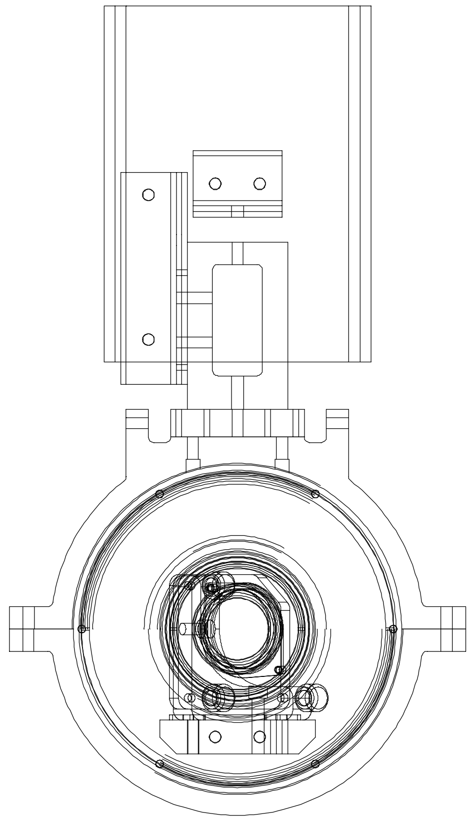

Figure 17: ETM Telescope, end view mechanical layout

2.3.5. ETM PO Beam Optical Relay System

A relay lens is used to image the entrance pupil of the ETM telescope onto an image plane on the ISC optical table. An ISC quad photodiode is placed an appropriate distance in front of the image plane to obtain a slightly defocussed image of the ETM entrance pupil. Motion of the centroid of energy on the photodiode is proportional to the motion of the IFO beam within the ETM mirror aperture. An optical schematic of the ETM PO beam optical relay system is shown in figure 18.

A 10% transmissivity ND filter is placed in the optical path to balance the scattered light noise from the photodetector.

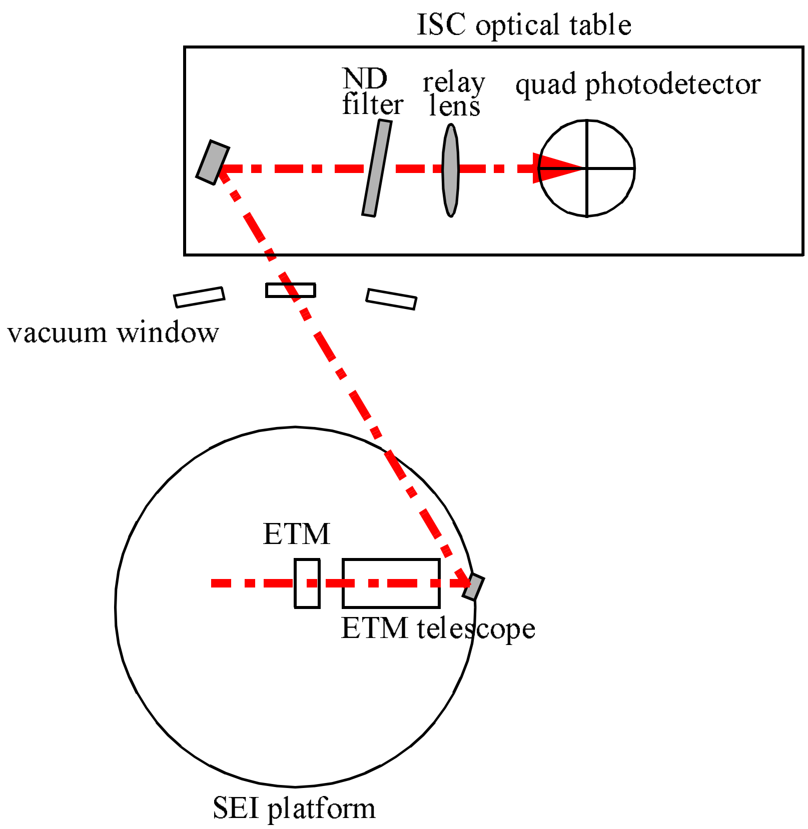

Figure 18: ETM PO beam optical system schematic diagram

ETM PO Telescope

input beam waist position, z_{11}	3090000 mm
input beam waist size, w_{011}	36.4 mm
distance to relay lens, d	2400 mm

Relay lens

primary focal length, f_3	151 mm

The location of the photodetector behind the relay lens to obtain a particular beam waist size on the photodetector is shown in figure 19.

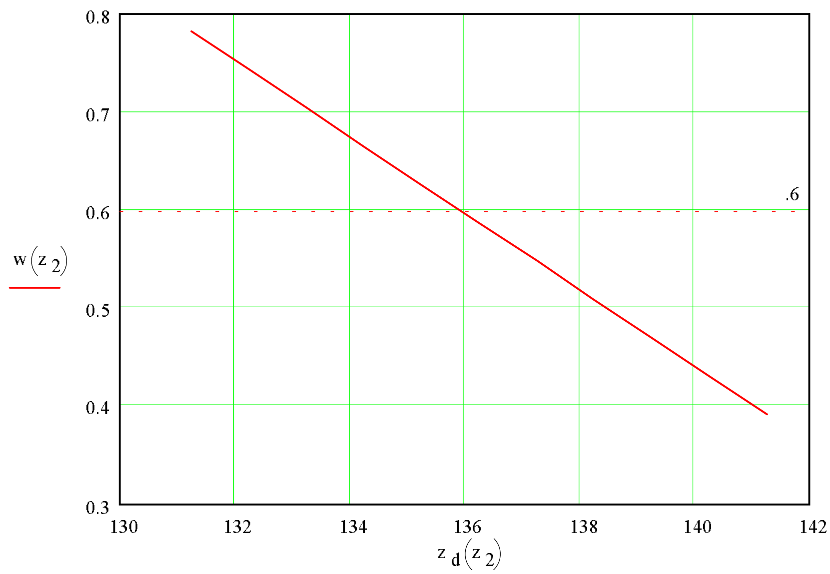

Figure 19: Beam waist size on the photodetector versus distance behind the relay lens, d=2400mm

2.3.5.1 Lateral Scale Factor

The lateral motion of the spot on the ETM photodetector is proportional to the lateral motion of the beam centroid at the surface of the ETM mirror by the factor 1/m. For example, a 0.1 mm shift on the ETM mirror will result in a shift a shift of the centroid on the photodetector of

$$x := \frac{0.1}{m} \qquad x = 8.397 \cdot 10^{-4}$$

millimeter.

2.3.5.2 Properties Of The ETM Relay Lens

Table 3: Properties of ETM Relay Lens

Parameter	*ETM Relay Lens*
total field of view	$\pm 1.5 \times 10^{-4} rad$
total clear aperture	26 mm
part number	Edmund Scientific p/n D32,501
focal length	150 mm
diameter	30 mm +0.00,-0.05

Table 3: Properties of ETM Relay Lens

Parameter	*ETM Relay Lens*
AR coating	>99% transmissivity @ 1064 nm

2.3.5.3 Neutral Density Filter In ETM PO Output Path

A 0.1 transmissivity neutral density filter must be placed in the ETM PO beam output path, as shown in figure 18, in order to attenuate the beam power to < 4 mW so that the scattered light from the quad photodetector does not exceed the COS budget (see COS Preliminary Design, T980010-01, table 1).

3 BAFFLES

3.1. Baffle Requirements

The requirements for the arm cavity baffle, elliptical baffle, and cryopump baffle are described in chapter 5 of COS Preliminary design, LIGO-T980010-01-D; and in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts, LIGO-T980103-00-D.

The mode cleaner baffle and input optic baffle, which is an extension of the mode cleaner baffle, do not have defined requirements. They are being placed in the general spirit of reducing scattered light from entering the recycling cavity section.

Table 4: Baffle Requirements

Parameter	*Required value*	*Measured value*	*Material*
BRDF of arm cavity baffle	$< 1\times10^{-2}\ sr^{-1}$	$1.4\times10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass
reflectivity of arm cavity baffle	< 0.09	9×10^{-4}	DESAG OG 14 filter glass
BRDF of elliptical baffle	$< 1\times10^{-2}\ sr^{-1}$	$1.4\times10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass with AR coating both sides
reflectivity of elliptical baffle	< 0.007	9×10^{-4}	DESAG OG 14 filter glass with AR coating both sides
resonant frequency of elliptical baffle	>160 Hz	238 Hz (calculated)	

Table 4: Baffle Requirements

Parameter	*Required value*	*Measured value*	*Material*
BRDF of mode cleaner baffle	not specified	$1.4 \times 10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass with AR coating one side
BRDF of input optics baffle	not specified	$1.4 \times 10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass with AR coating one side
BRDF of cryopump baffle	$< 1 \times 10^{-2}\ sr^{-1}$	$1 \times 10^{-3}\ sr^{-1}$	oxidized stainless steel

3.2. Arm Cavity Baffle

3.2.1. Arm Cavity Baffle Final Design

3.2.1.1 ITM Baffles, Vertex Station

Arm cavity baffles will be placed in the vertex station in the x and y arms between the ITM mirror and ETM mirrors. The baffles are located in the BE-5 and BE-6 manifold tubes. The baffle surface is IR absorbing glass aligned nominally at Brewster's angle for the horizontally polarized scattered light from the ETM. A view of the baffle and mounting structure as seen looking toward the ITM is shown in figure 20.

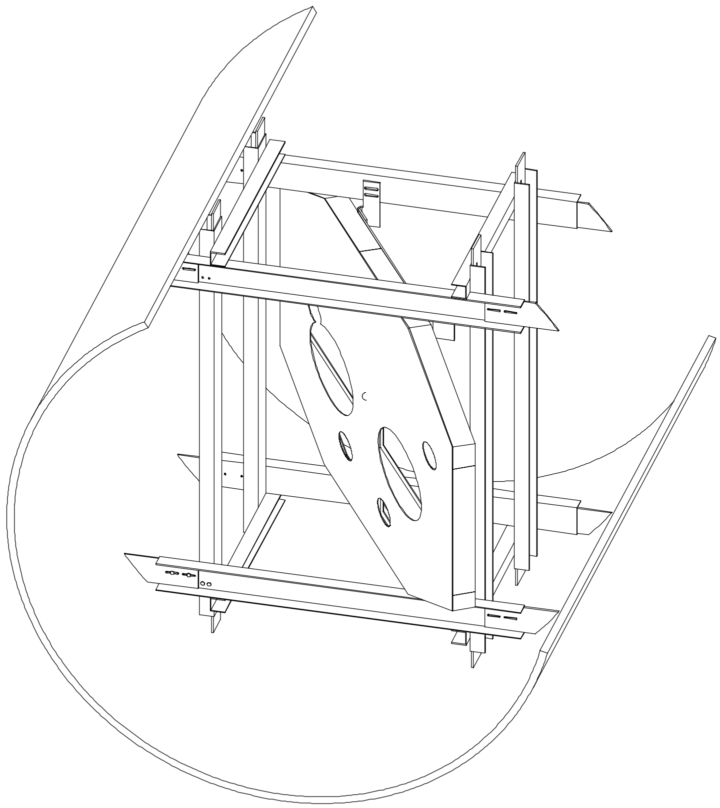

Figure 20: View of ITMx baffle looking toward the ITM

A view of the baffle and mounting structure as seen looking toward the ETM is shown in figure 21. The mounting structure for the baffle material does not interfere with the ghost beams.

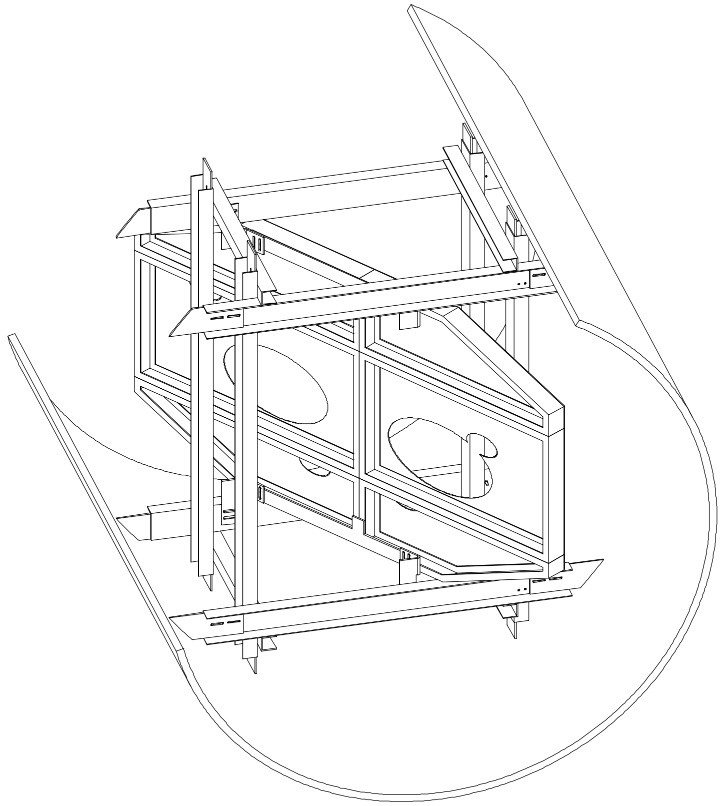

Figure 21: View of ITMx baffle looking toward the ETM

The back side of the baffles also function as beam dumps for the ITMHR3 and ITMHR4 ghost beams. Optical apertures are cut through the baffle surface to allow passage of the 2K and 4K main beams, as well as the optical lever beams for the 2K and 4K ITM mirrors, as shown in figure 22. See "Design of Special Beam Dump, BD GB 2KITMHR3 and BD GB 2KITMHR4" on page 49.

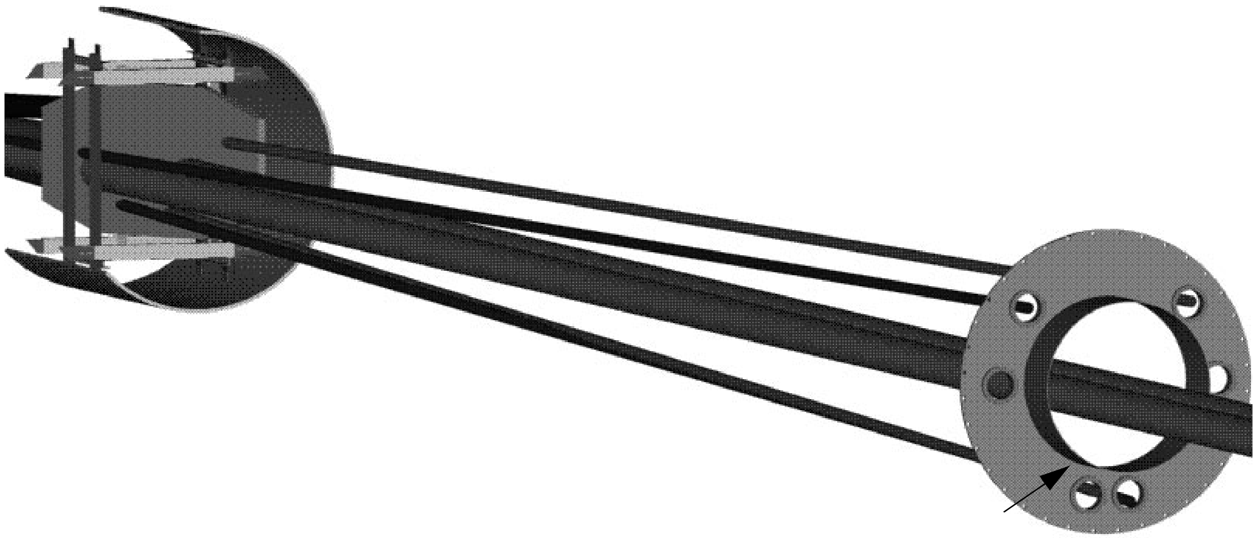

Figure 22: ITM arm cavity baffle, showing passage of optical lever beams and main beams for 2K and 4K IFO

3.2.1.2 ETM Baffles, End Station

The arm cavity baffles placed in the end station in the x and y arms between the ITM mirror and the 4K ETM mirror are located in the A-7A2 and A-7B2 manifold tubes, as shown in figure 23.

Optical apertures are cut through the baffle surface to allow passage of the 4K main IFO beams, as well as the optical lever beams for the 4K ETM mirrors. The baffle also occludes the view of the cryopump cold surface from the 4K ETM mirror, and therefore eliminates the need of a cryopump baffle in the end station.

During initial lock acquisition phase, the misaligned main beam passing through the ITM and heading toward the ETM will reflect from the surface of the baffle and will hit the inside wall of the A-7 manifold. The surfaces where the beam hits the manifold wall can be viewed through one of the horizontal viewing ports in the spool pieces A-1E and A-1F.

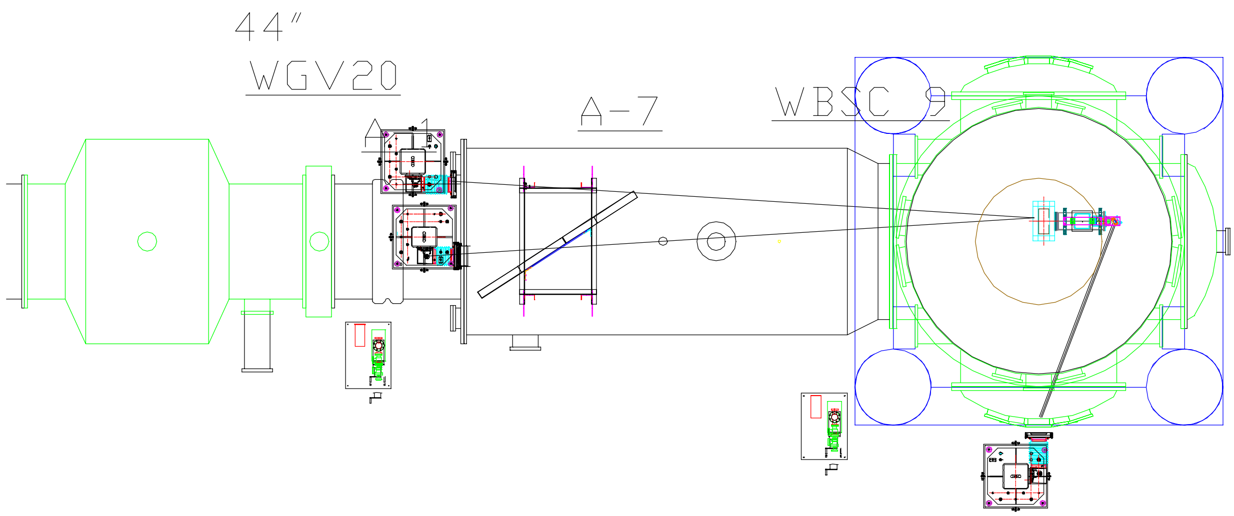

Figure 23: ETM arm cavity baffle in the end station

3.3. Recycling Cavity Elliptical Baffle

3.3.1. Elliptical Baffle Final Design

Elliptical baffles are attached to the LOS structure for the RM, ITMx, and ITMy in the 2K and 4K IFO facing toward the BS. The elliptical hole is 3mm larger on every side around the elliptical cross section of the BS mirror, which is rotated by 45 deg. The baffles will be attached after the LOS structure has been mounted and aligned on the SEI platform.

The 4K ITMx elliptical baffle is shown in figure 24. The baffle mounts to the LOS structure, and is tilted 5 deg to avoid a direct retroreflection into the IFO. The baffle is made of IR absorbing glass with an AR coating @ 1064 nm. An additional IR absorbing glass surface is placed above the elliptical baffle to function as a LOS-mounted beam dump for the BSAR3 ghost beam (See "Design of LOS-mounted Beam Dump for Ghost Beam 4K BSAR3" on page 42.). The beam dump surface is angled to reflect the residual ghost beam towards the ITMxAR3 beam dump.

A preliminary estimate of the fundamental vibration frequency of the elliptical baffle was calculated[1]. The results indicated that with the baffle simply supported at the four corners, the drum head resonant frequency is 242 Hz. The requirement for the minimum resonant frequency of an object directly mounted to the LOS structure is > 160 Hz. Therefore the elliptical baffle design appears to be acceptable.

1. D. Coyne, COS Elliptical lBaffle Vibration ANalysis, preliminary, verbal communication

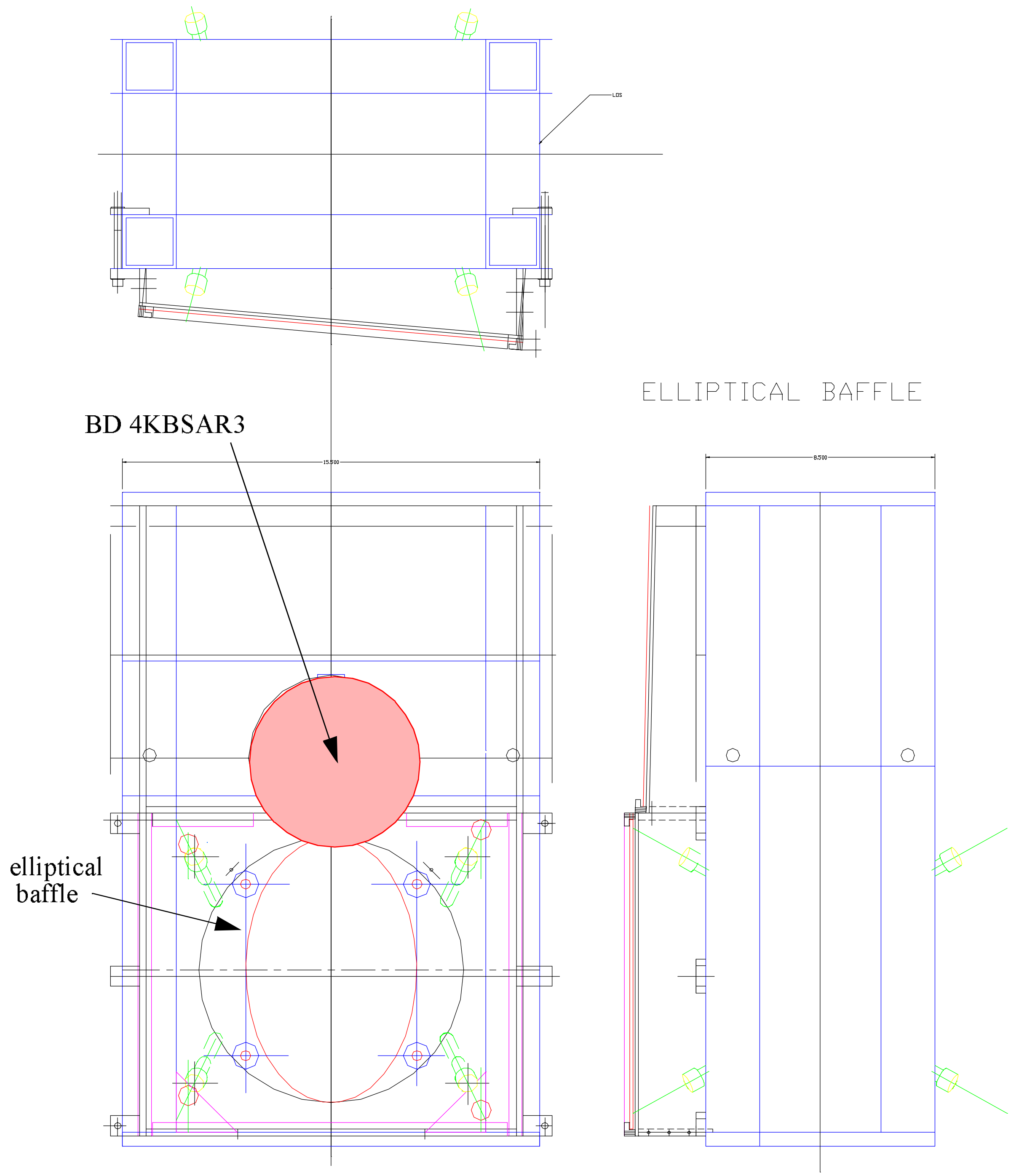

Figure 24: Elliptical baffle, and LOS-mounted beam dump for 4K BSAR3 ghost beam

3.3.2. Annular Baffle for Arm Cavity Scattered Light

The back side of the elliptical baffle also serves to catch the arm cavity scattered light, which passes through the annular region formed by the diameter of the ITM mirror and the inside diameter of the main IFO beam clearance hole in the arm cavity baffle in the vertex station.

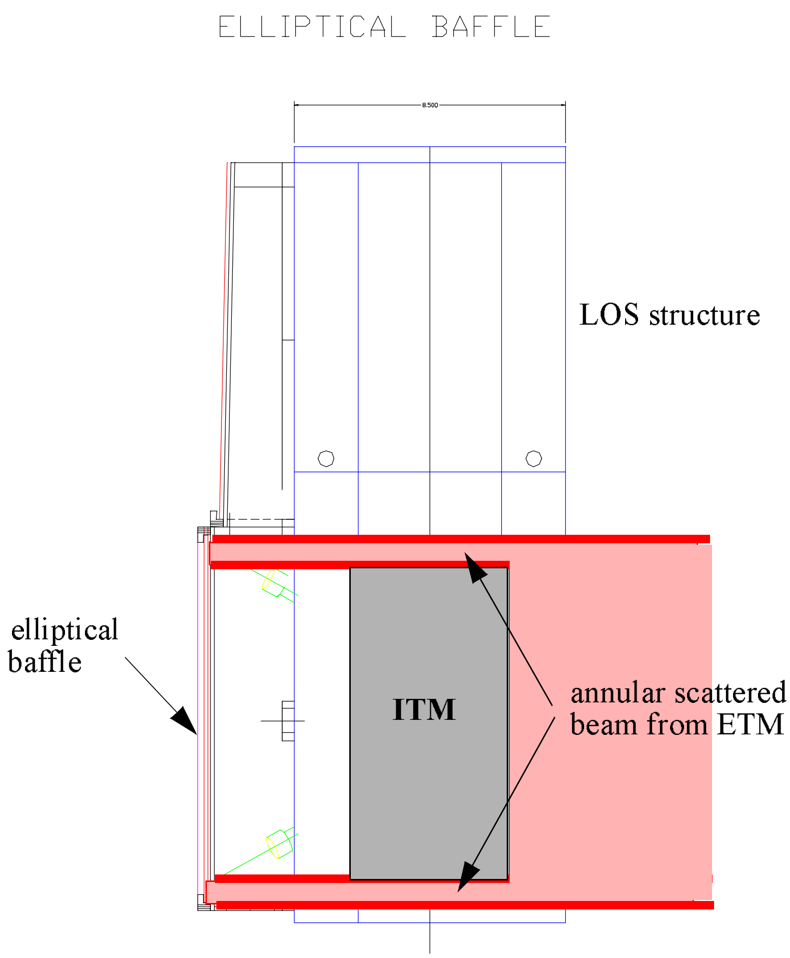

Figure 25: Annular Baffle for arm cavity scattered light

3.4. Mode Cleaner Baffle

3.4.1. Mode Cleaner Baffle Final Design

The scattered light from the surfaces of the mode cleaner mirrors will form an annular beam passing predominantly around the periphery of mirrors MC1 and MC2, as shown schematically in figure 26. An absorbing glass baffle will be mounted to the MC1 SOS structure to absorb part of the scattered light. The remainder of the scattered light, passing around MC2 will be absorbed in the IO baffle which is placed behind MC2 in HAM8 and in HAM2.

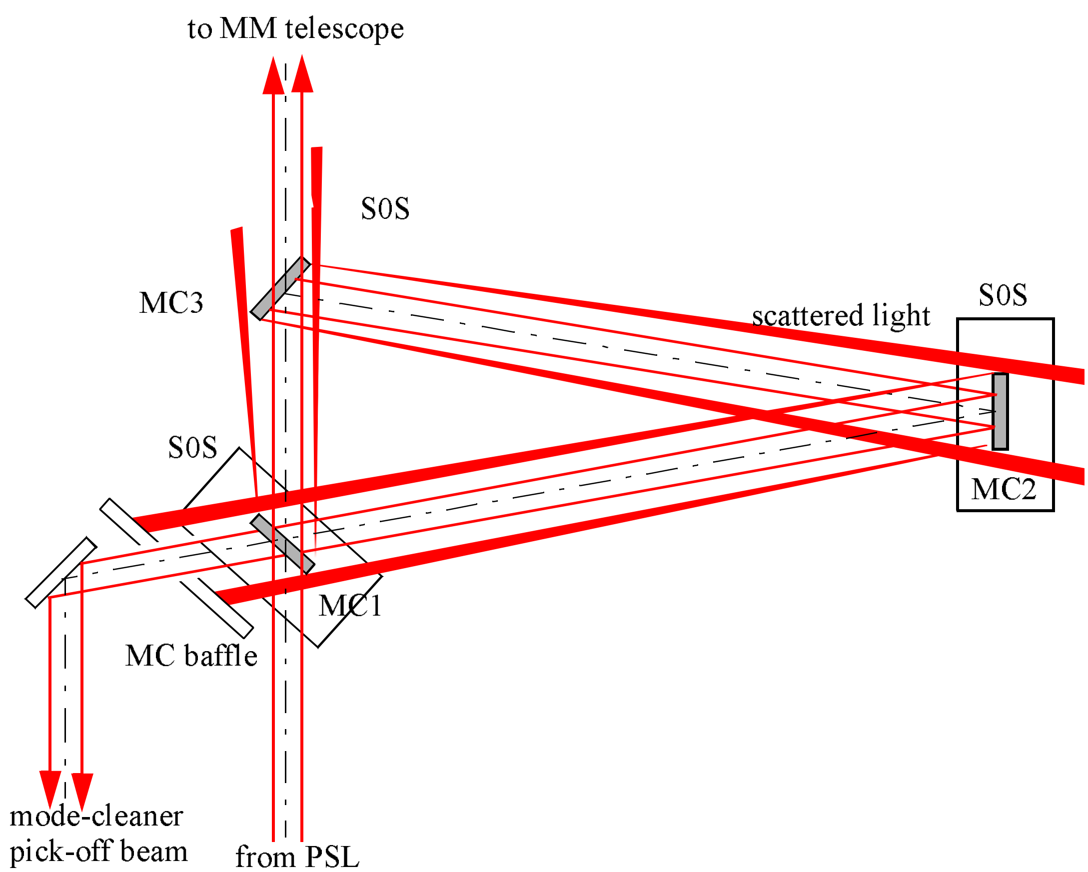

Figure 26: Mode cleaner baffle on MC1 SOS

3.5. Input Optics Baffle

3.5.1. Input Optics Baffle Final Design

The input optics baffle design is similar to the arm cavity baffle. The absorbing glass plate is mounted to a ribbed support structure, which in turn is mounted to the walls of the HAM2 and HAM8 chambers. The baffle in HAM2 has holes cut in the glass for passage of the 4K IFO main-beam and for passage of the optical lever beams for the 4K RM mirror in HAM3, as shown in figure 27.

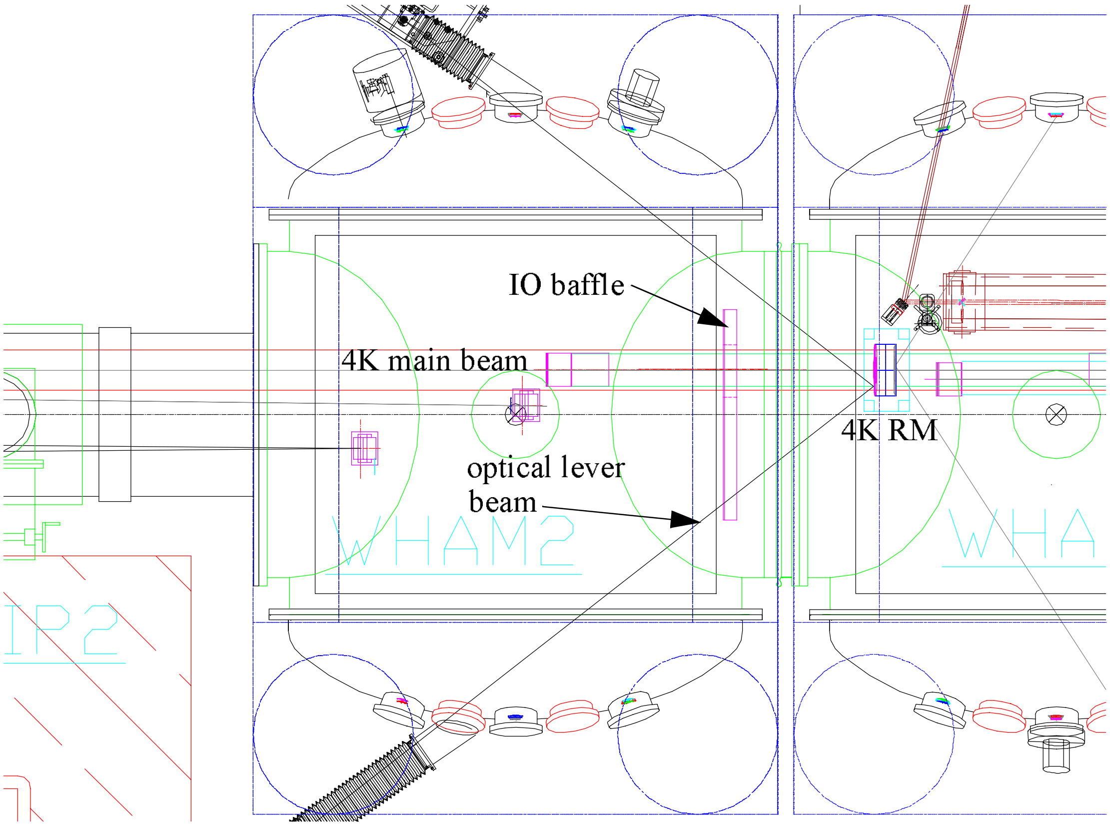

Figure 27: Input Optics Baffle

3.6. Cryopump Baffles

3.6.1. Cryopump Conical Baffle Final Design

Conical cryopump baffles will be placed in the A-1A and A-1B spool pieces in front of the cryopumps to occlude the cold surface of the cryopump from visibility by the scattered light from the vertex station ITMx and ITMy mirrors.

The cryopump baffles are construacted of the same stainless steel material with an oxide layer that is used for the beam tube baffles. A circumferential expansion joint with slotted holes allows the baffle mounting ring to expand against the insides of the spool piece for mounting.

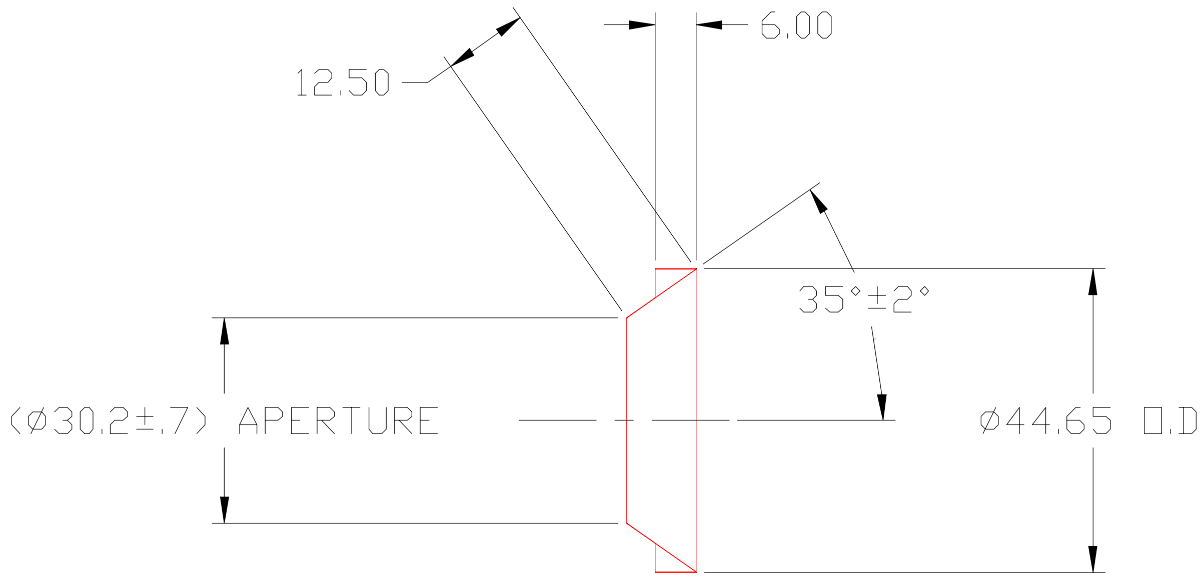

Figure 28: Cryopump conical baffle

3.6.2. Cryopump Manifold Baffle, Mid Station, Final Design

Arm cavity baffles will be placed in the A-7A and A-7B manifold tubes in the mid station in the x and y arms between the cryopump and the 2K ETM mirror. The purpose of the baffle is to occlude the view of the cryopump cold surface from the 2K ETM mirror, and therefore eliminate the need of a cryopump baffle in the mid station.

The surfaces of the baffle facing the cryopump and facing the 2K ETM mirror are IR absorbing glass aligned nominally at Brewster's angle. The internal structure of the baffle is hidden by the glass surfaces so that the scattered light from the ITM headed toward the 2K ETM and the scattered light from the 4K ETM headed toward the ITM can not hit the metal structure of the baffle. Optical apertures are cut through the baffle surfaces to allow passage of the 2Kmain IFO beam, as well as the optical lever beams for the 2K ETM mirrors, as shown in figure 29.

During initial lock acquisition phase, the misaligned main beam passing through the ITM and heading toward the ETM will reflect from the surface of the baffle and will hit the inside wall of the A-7 manifold. The surfaces where the beam hits the manifold wall can be viewed through one of the horizontal viewing ports in the spool pieces A-1C and A-1D.

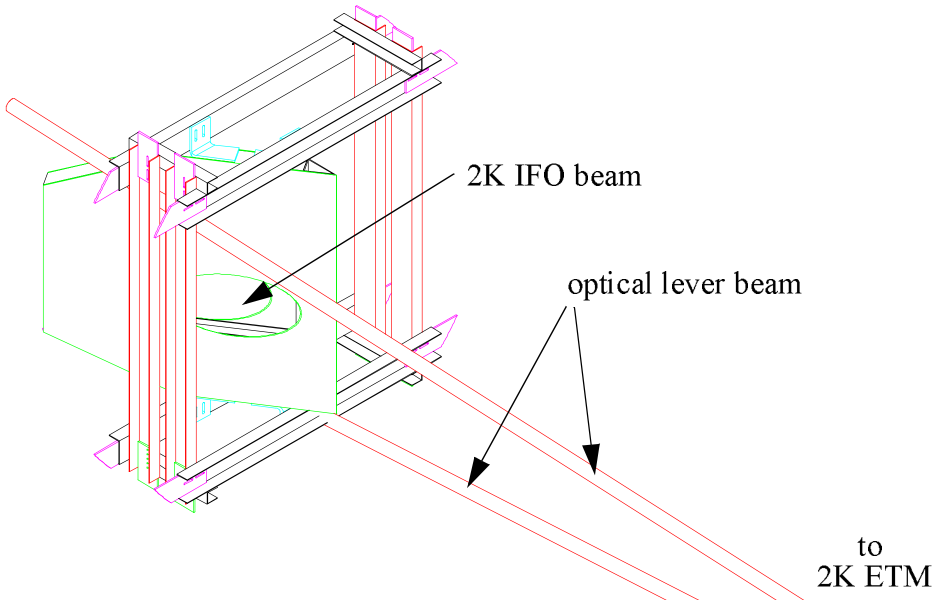

Figure 29: Mid station cryopump arm cavity baffle, showing passage of optical lever beams and main beam for 2K IFO

4 BEAM DUMPS

4.1. Mounting Height Range Due to COC wedge angle tolerance

The locations of the beam dumps, and the height range due to the ±5 min COC wedge angle tolerance are shown in Table 5 on page 38.

4.2. Cavity Beam Dump

A cavity beam dump is used to dump the following ghost beams: 4K GB ITMYAR1, 4K GB ITMYAR4, 4K GB ITMXAR1, 4K GB ITMXAR4, 4K GB ITMYHR3, 4K GB ITMYHR4, 4K GB ITMXHR3, 4K GB ITMXHR4, 2K GB ITMYAR1, 2K GB ITMYAR4, 2K GB ITMXAR1, 2K GB ITMXAR4.

4.2.1. Cavity Beam Dump Optical Requirements

The optical requirements for the cavity beam dump are described in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts LIGO-T980103-00-D, and are listed in Table 6 on page 39.

Table 5: Beam Dump Locations

BEAM DUMP	*Beam Dump Global Coordinates, mm*			*Beam dump height tolerance, mm*	*Beam dump pitch, deg*
	X	*Y*	*Z*		
2K ITMXAR1	9165	8200	-276	-30.0	1.2
2K ITMXAR4	9161	8150	478	76.0	-4.0
2K ITMXHR3				14.5	
2K ITMXHR4				29.0	
2K ITMYAR1	8003	9074	-261	-27.8	1.2
2K ITMYAR4	8003	9070	460	71.0	-4.1
2K ITMYHR3				14.5	
2K ITMYHR4				29.0	
2K RMHR3	10500	9060	-204	7.5	8.0
2K FMXX	8600	-231	-124	0.0	-1.4
2K FMXY	9131	-799	-104	0.0	0.5
2K FMYX	-750	9041	-105	0.0	-0.5
2K FMYY	168	8511	-122	0.0	-1.4
2K BSAR3	1249	9033	262	38.6	-2.0
2K BSHR3P-2	10201	9102	190	23.2	-4.2
2K BSHR3P-1	12584	9100	240	14.4	-4.2
4K ITMXHR3	8350	199	120	15.9	-3.4
4K ITMXHR4	8330	199	349	31.6	-6.8
4K ITMYHR3	-199	8400	118	15.5	-3.4
4K ITMYHR4	-199	8302	332	30.3	-6.8
4K ITMYAR1	-199	1000	-283	-13.2	2.9
4K ITMYAR4	-199	1099	389	32.9	-7.7
4K ITMXAR1	100	199	-275	-16.0	2.2
4K ITMXAR4	1147	199	363	31.2	-7.7
4K BSAR3	4430	235	104	22.6	-2.0

Table 6: Cavity Beam Dump Optical Requirements

Parameter	*Required value*	*Measured value*
net reflectivity	$<5\times10^{-3}$	$< 3.9\times10^{-8}$
reflectivity per bounce	$<7\times10^{-2}$	9×10^{-4}
number of bounces	>2	4
material		DESAG OG 14 filter glass
BRDF	$< 1\times10^{-2}\ sr^{-1}$	$<1.4\times10^{-4}\ sr^{-1}$

4.2.2. Cavity Beam Dump Mechanical Resonance Requirements

The mechanical resonances of the beam dump structure will increase the amplitude of vibration of the seismic noise by the factor Q, the inverse damping factor. When the vibration amplitude approaches $\frac{\lambda}{8}$, the onset of fringe-wrap occurs and the vibration motion becomes frequency shifted to higher odd harmonics of the fundamental resonance frequency of the beam dump.

The mechanical resonance requirements for the cavity beam dump are analyzed in Up-conversion of Scattered Light Phase Noise from Large Amplitude Motions, LIGO-T980101-00D and are listed in Table 7 on page 39. The design frequency for the cavity beam dump was chosen to be > 100 Hz to eliminate fringe-wrap effects with standard LIGO ground motion.

Table 7: Cavity Beam Dump Mechanical Resonance Requirements

Parameter	*Required value*	*Measured value*
inverse damping factor, Q	<100	TBD
onset of fringe-wrap, frequency @ Q=100	8 Hz	
minimum frequency to eliminate fringe-wrap noise	>25 Hz, for std LIGO ground motion spectra	
maximum Q for negligible beam dump phse noise, @ BRDF= $1\times10^{-2}\ sr^{-1}$	<100	TBD
minimum design resonant frequency	> 25 Hz	>100 Hz (calculated)

4.2.3. Cavity Beam Dump Final Design

A top view and side view of the double cavity beam dump design is shown in figure 30.

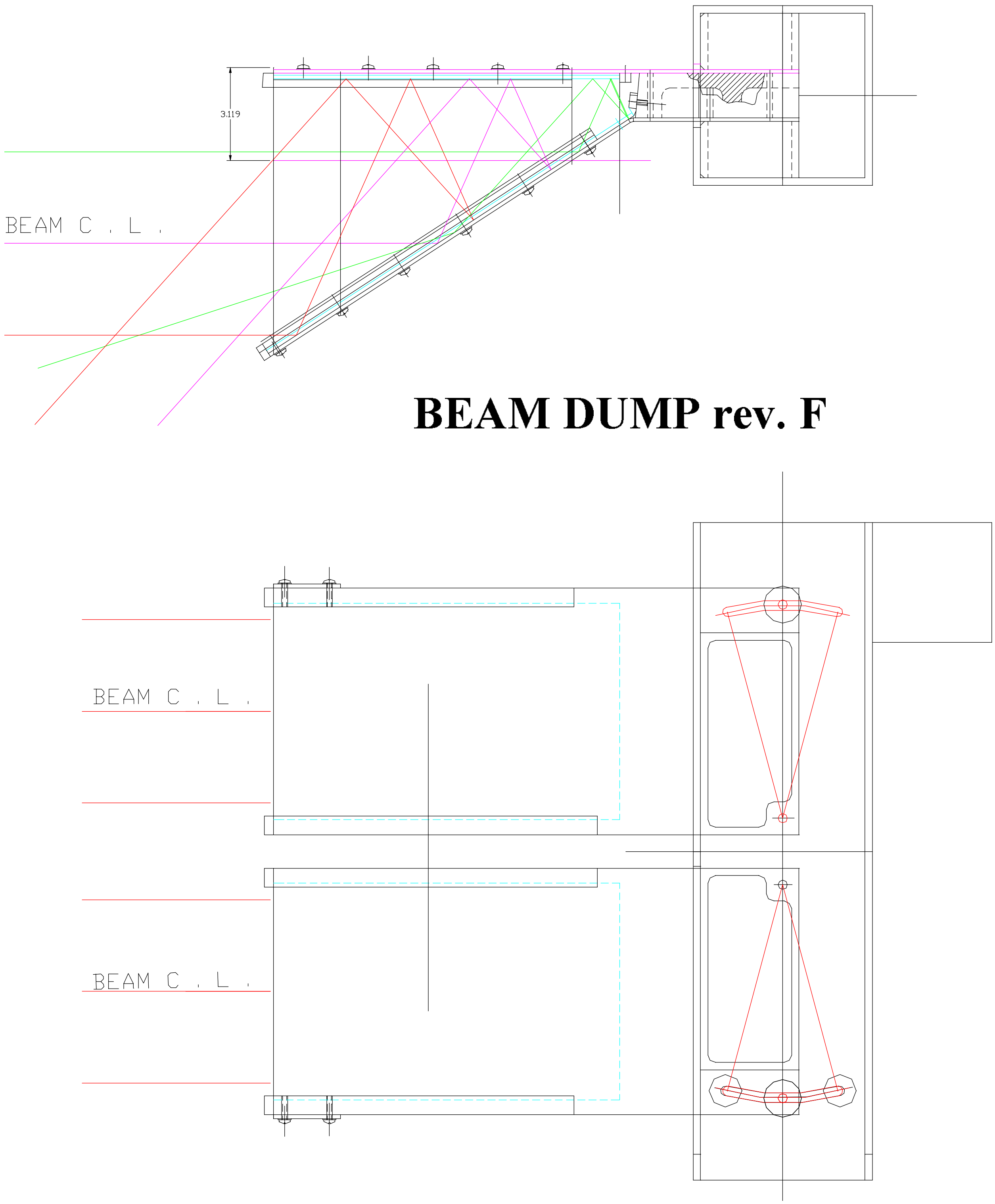

Figure 30: Double cavity beam dump

This particular configuration is used to dump the 4K IFO ghost beams ITMHR3, and ITMHR4. The ghost beam makes four internal reflections within the cavity before exiting. The first reflection is at Brewster's angle, so the beam will be highly absorbed by the IR absorbing glass. A single cavity beam dump consists of only one cavity. The Beam dump is mounted to a horizontal support beam. Slotted mounting holes allow horizontal and vertical alignment of the beam dump location.

The estimated resonant frequencies of the beam dump assembly are compatabile with the COS ghost beam noise requirements. See Up-conversion of Scattered Light Phase Noise from Large Amplitude Motions, LIGO T980101-00-D.

4.2.3.1 Triple Hinge Bracket

The horizontal support beam is attached to the mounting brackets on the BSC and HAM chamber walls by means of a triple hinge joint, comprised of a single hinge bracket on one side of the horizontal support beam and a double hinge bracket on the other end, as shown in figure 31. This allows radial compression of the chamber walls while maintaining the torsional rigidity of the horizontal support beam. The magnitude of the radial distortion was calculated with a finite element analysis. See Determination of Deflection Requirements for BSC Support Beam Bellows, HYTEC-TN-LIGO-08a.

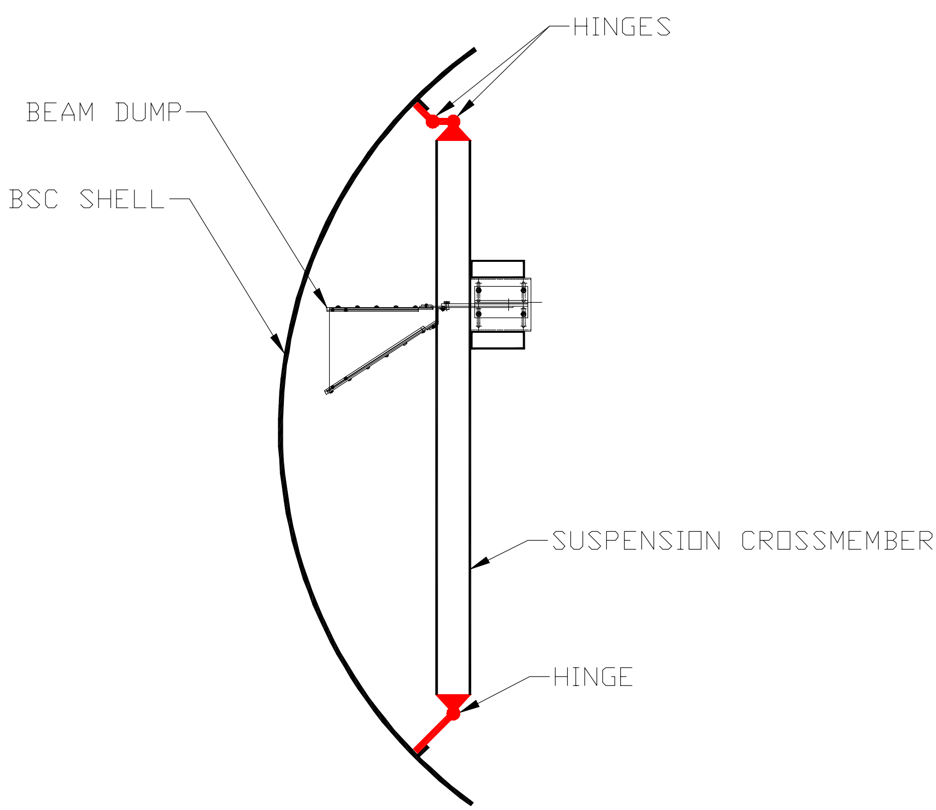

Figure 31: Triple hinge joint for attaching the beam dump horizontal support beam to the BSC chamber

4.3. LOS-mounted Beam Dump

In some cases the ghost beam does not clear sufficiently far from the main beam and it is necessary to place an absorbing glass plate beam dump directly onto the COC LOS structure. An LOS-mounted beam dump is used for dumping the following ghost beams: GB 4KBSAR3, GB 4KBSHR3P, GB 2KBSHR3P.

4.3.1. Requirements for LOS-mounted Beam Dumps

The requirements for the LOS-mounted beam dumps are described in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts LIGO-T980103-00-D, and are listed in Table 8 on page 42.

Table 8: Requirement for LOS-mounted Beam Dump

Parameter	*Required value*	*Measured value*	*Material*
BRDF	$<0.01 sr^{-1}$	$1.4\times10^{-4} sr^{-1}$	DESAG OG 14 filter glass with AR coating
reflectivity	< 0.12	$< 3.5\times10^{-2}$	DESAG OG 14 filter glass with AR coating
resonant frequency	>160 Hz	238 Hz (calculated)	

4.3.1.1 Design of LOS-mounted Beam Dump for Ghost Beam 4K BSAR3

A detail view of the beam dump mounted to the LOS structure is shown in figure 32. Most of the ghost beam hits the beam dump surface and is absorbed by the IR absorbing glass with an AR coating. An elevation view of the LOS-mounted BD 4KBSAR3 in BSC3 is shown in figure 33.

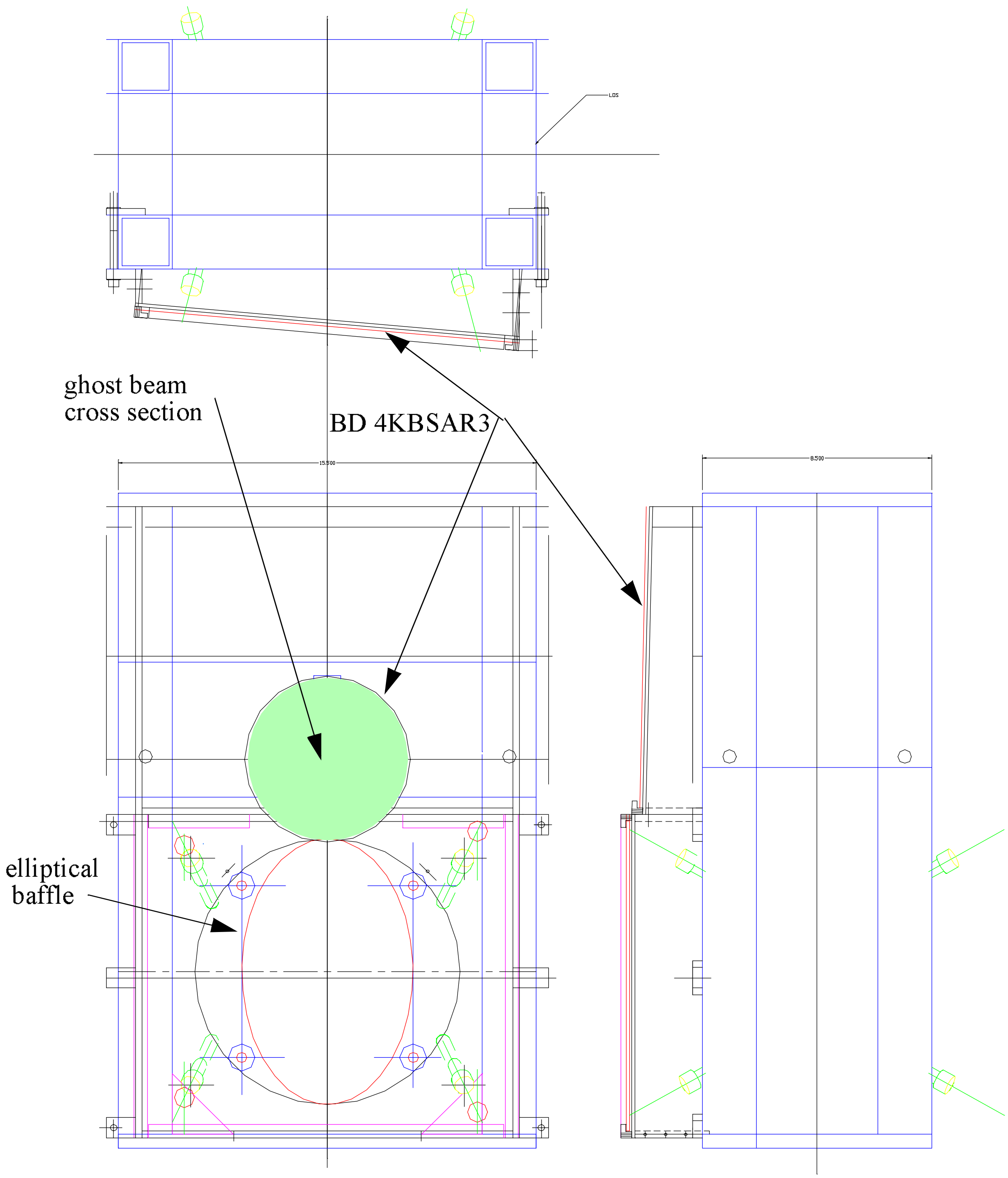

Figure 32: Detail of LOS-mounted beam dump

.

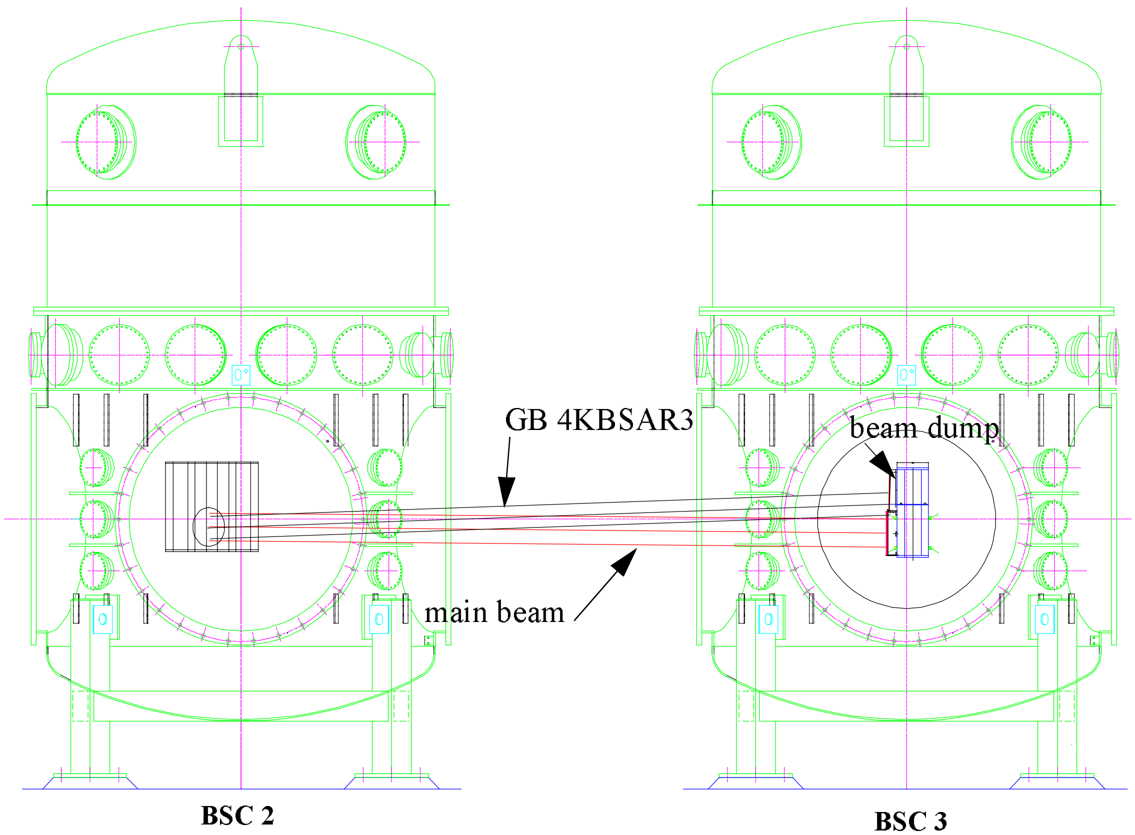

Figure 33: LOS-mounted beam dump for GB 4KBSAR3

4.3.1.2 Design of LOS-mounted Beam Dump for Ghost Beam 4K BSHR3P

The design of beam dump 4KBSHR3P is identical to the 4KBSAR3 beam dump shown in the detail view in figure 32. The GB 4K BSHR3P hits the beam dump surface which is mounted directly on the 4KRM LOS structure in HAM3. The AR-coated glass surface absorbs most of the energy, and is tilted to reflect the remainder away from the IFO beam.

4.3.1.3 Design of LOS-Mounted Beam Dump for Ghost Beam 2K BSHR3P

The GB 2KBSHR3P partially hits the RM on HAM9 and is reflected toward the BD BSHR3P-2 located on BSC4, as shown in figure 34.. Part of GB 2KBSHR3P hits the beam dump surface BD BSHR3P-1 which is mounted directly on the RM LOS structure above the elliptical baffle. The glass surface absorbes most of the energy, and is tilted to reflect the remainder toward BD BSHR3-2, The design of BD BSHR3P-1 is identical to the 4KBSAR3 beam dump shown in the detail view in figure 32.

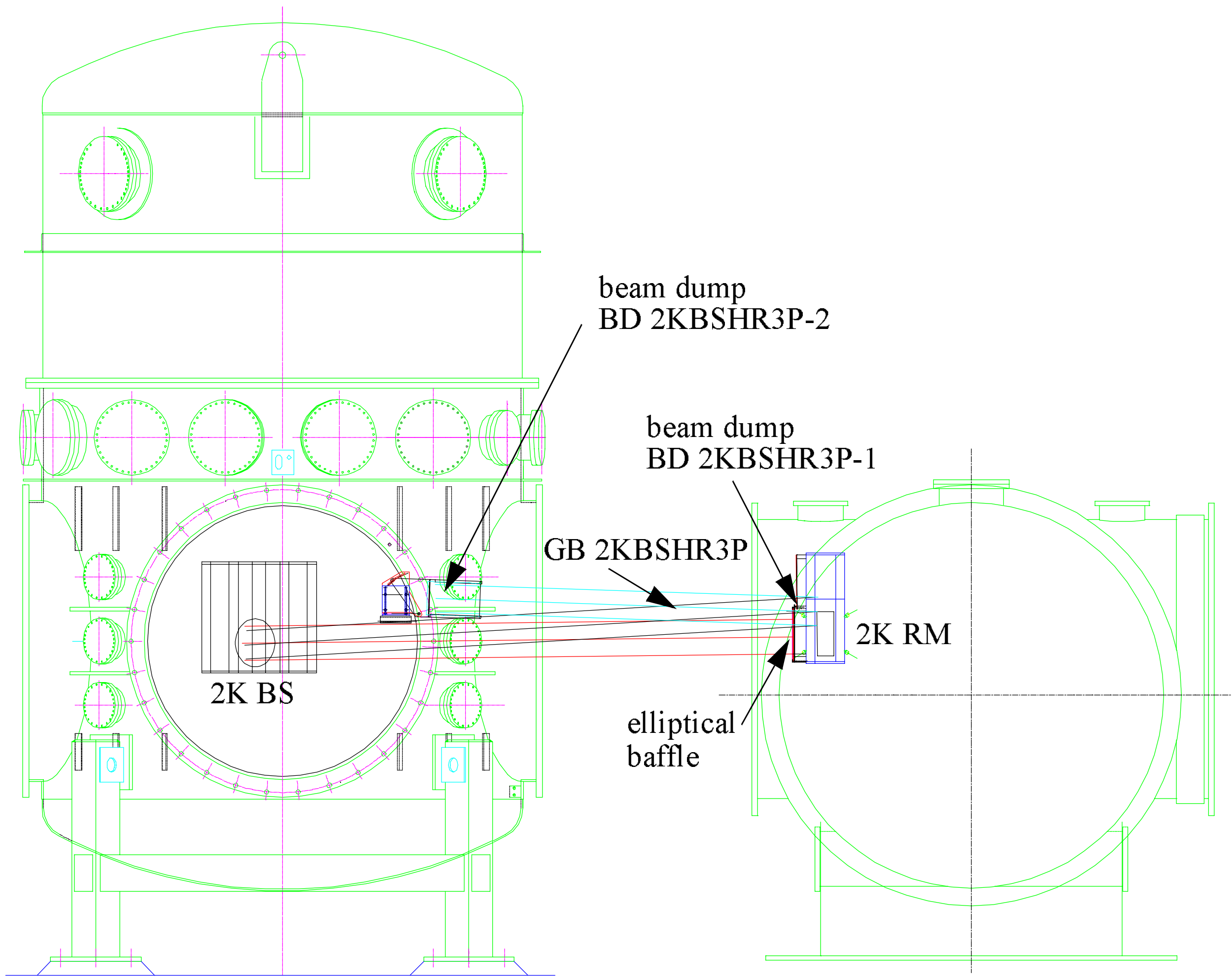

Figure 34: LOS-mounted Beam Dump for Ghost Beam 2K BSHR3P

4.4. SEI-mounted Beam Dump for Ghost Beam 4K RMHR3

The beam dumps for GB 4K RMHR3 and GB 2K RMHR3 are mounted directly on the SEI platform in HAM3 and HAM9.

4.4.1. Requirement for SEI Beam Dump

The requirements for the SEI beam dump is described in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts LIGO-T980103-00-D, and are listed in Table 9 on page 46

Table 9: Requirement for SEI-mounted Beam Dump

Parameter	*Required value*	*Measured value*	*Material*
BRDF 3	<0.01	$1.4\times10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass
reflectivity of BD GB 4K BSAR3	<1	3.5×10^{-2}	DESAG OG 14 filter glass

4.4.1.1 Design of SEI-mounted Beam Dump, Ghost Beams 4KRMHR3, 2KRMAR3

BD GB 4K RMHR3 consists of a flat piece of absorbing glass mounted to the SEI platform of HAM3 with an inclined protruding plate to catch the reflected beam, as shown in figure 36. A detail of the beam dump is shown in figure 35.

The design for the BD 2K RMAR3 in HAM9 is similar.

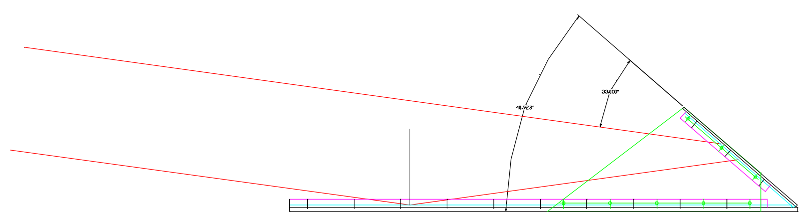

Figure 35: Detail of SEI-mounted beam dump BD 4KRMHR3

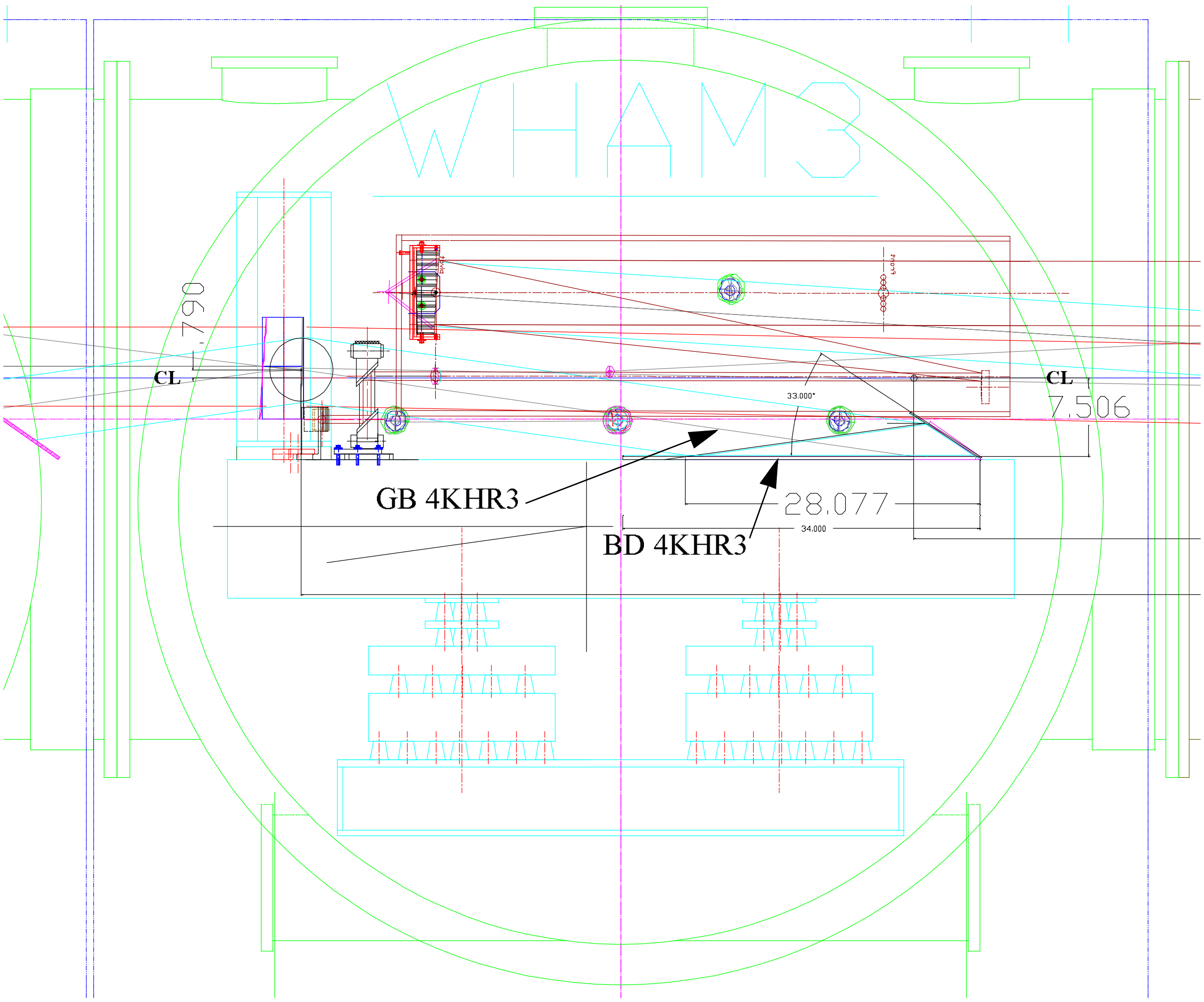

Figure 36: SEI-mounted Beam Dump for Ghost Beam 4K RMHR3

4.5. Vacuum Window Beam Dump

The reflected PO beams from the surfaces of the output windows will be dumped on a beam dump attached to the sides of the SEI platform in HAM3, HAM4, HAM9, HAM10.

4.5.1. Requirement for Vacuum Window Beam Dump

The requirements for the vacuum window beam dump are described in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts LIGO-T980103-00-D, and are listed in Table 10 on page 48

Table 10: Requirement for Vacuum Window Beam Dump

Parameter	*Required value*	*Measured value*	*Material*
BRDF	<0.01	$1.4\times10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass with AR coating
reflectivity	<0.7	3.5×10^{-2}	DESAG OG 14 filter glass with AR coating

4.5.2. Design of Vacuum Window Beam Dump

The vacuum window beam dump consists of an absorbing glass plate attached to the sides of the SEI platform in HAM3, HAM4, HAM9, HAM10, as shown in figure 37. The beam will partially reflect from the beam dump, and will scatter from the chamber walls diffusing the return path into the IFO to a safe level.

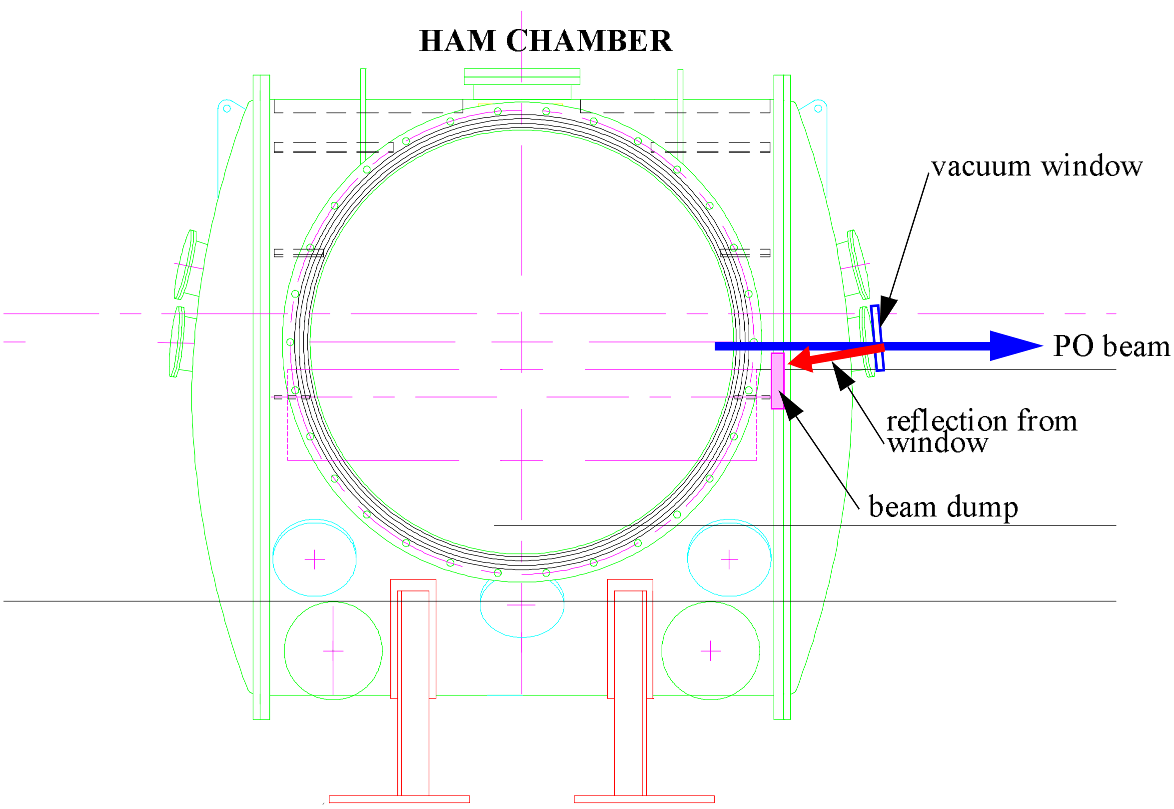

Figure 37: Detail of vacuum window beam dump

4.6. Special Beam Dumps

4.6.1. Beam Dump for 2K ITMHR3 and 2KITMHR4 Ghost Beams

The 2K ITMHR3 and ITMHR4 ghost beams are dumped on the back surface of the ITM arm cavity baffles located in manifold sections B-1A, and B-1B.

4.6.1.1 Requirements for BD 2KITMHR3 and BD 2KITMHR4

The requirements for the beam dump are described in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts LIGO-T980103-00-D, and are listed in Table 11 on page 49.

Table 11: Requirements for 2K ITMHR3 and 2K ITMHR4 Beam Dump

Parameter	*Required value*	*Measured value*	*Material*
BRDF of BD GB 2K ITMHR3	$<8\times10^{-2}\ sr^{-1}$	$1.4\times10^{-4}\ sr^{-1}$	DESAG OG 14 filter glass
reflectivity of BD GB 2KITMHR3	$< 9\times10^{-1}$	$< 9\times10^{-4}$	DESAG OG 14 filter glass

4.6.1.2 Design of Special Beam Dump, BD GB 2KITMHR3 and BD GB 2KITMHR4

A three dimensional layout of the beam dump is shown in figure 38.

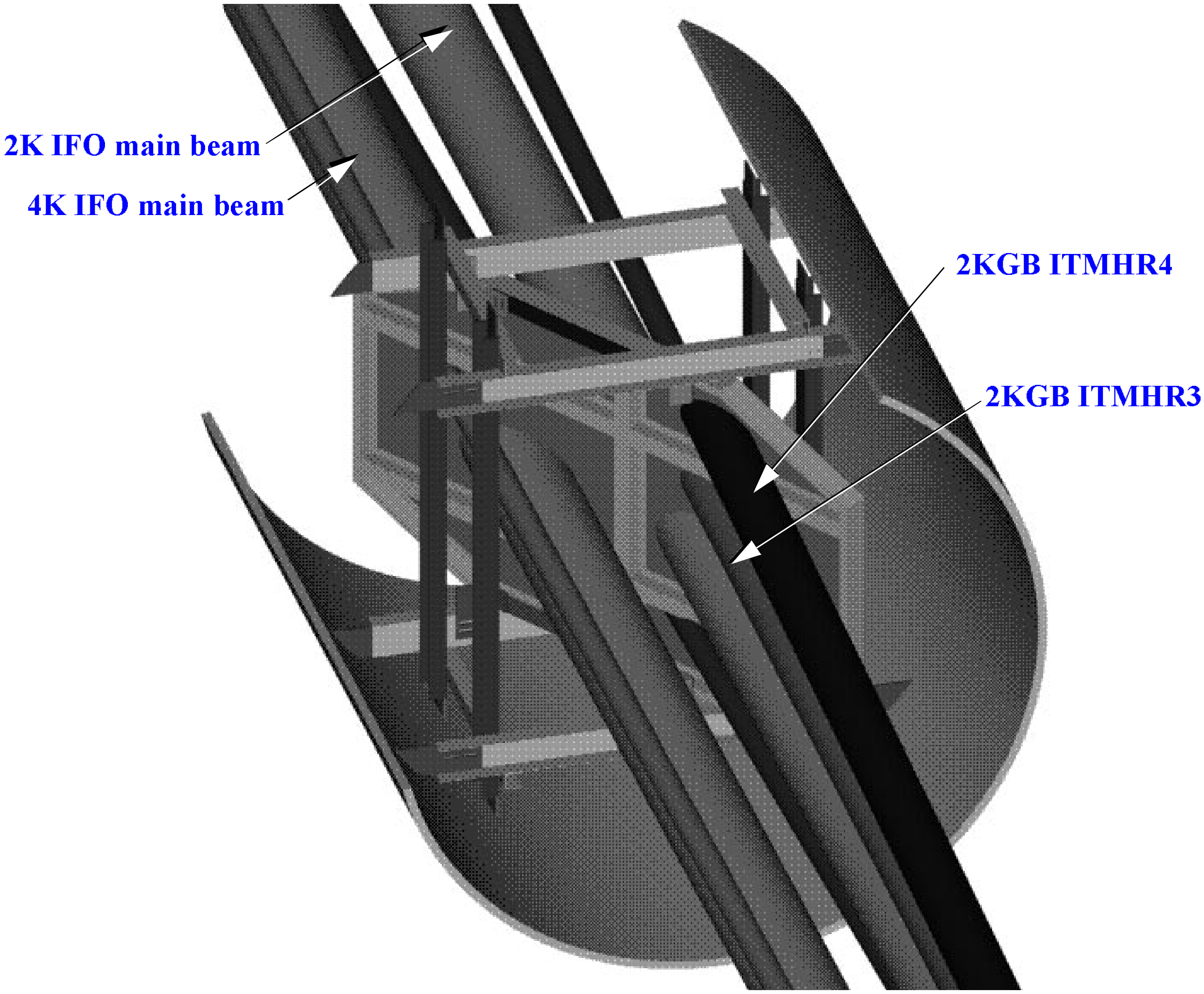

Figure 38: 2KITMHR3 and 2KITMHR4 beam dumps on back of ITM arm cavity baffle

4.6.2. Telescope Beam Dump for Ghost Beams 4KBSAR1P and 4KBSAR3P

An IR absorbing glass plate will be mounted to the entrance aperture of the APS PO telescope. A portion of the ghost beams will enter the PO telescope, and will be trapped by internal baffles

4.6.2.1 Requirements for Telescope Beam Dump, BD 4KBSAR1P and BD 4KBSAR3P

The requirements for the telescope beam dump are described in COS Beam Dump and Stray Light Baffle Revised Requirements and Concepts LIGO-T980103-00-D. The requirements are the same as the LOS-mounted beam dump. See “Requirement for LOS-mounted Beam Dump” on page 42.

4.6.3. Design of Telescope Beam Dump for Ghost Beams 4K BSAR1P and

4K BSAR3P

The IR absorbing glass plate on the front of the telescope will absorb most of the ghost beams 4K BSAR1P and 4K BSAR3P, and reflect some of the energy to the chamber walls; the internal baffles will trap the ghost beams which enter the PO telescope, as shown in figure 39.

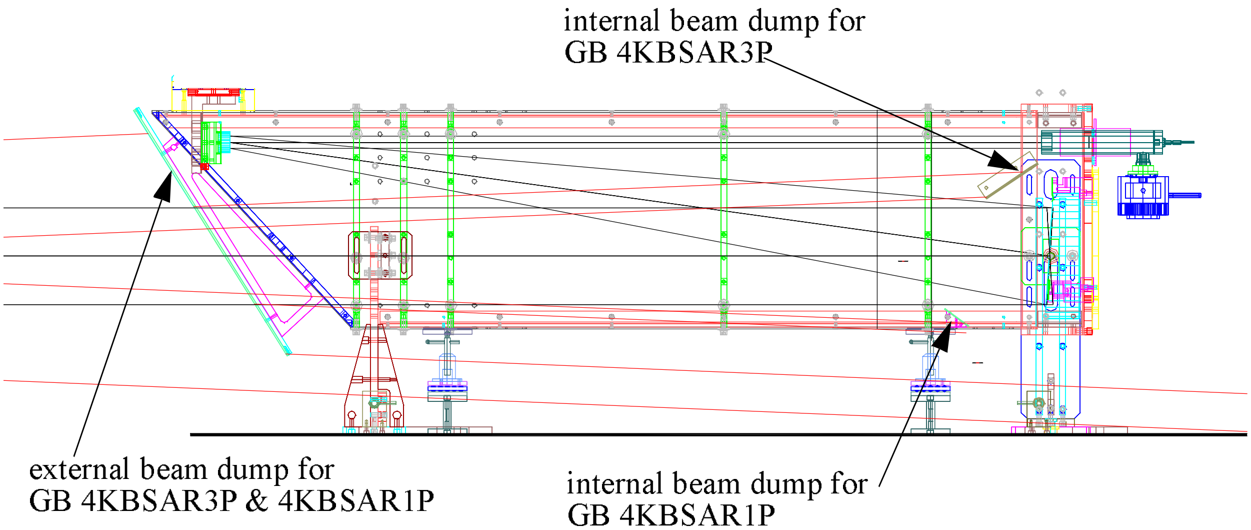

Figure 39: PO Telescope with internal beam dumps

4.6.4. Design of Telescope Beam Dump for Ghost Beams 2KETMAR3 and 4KETMAR3

The ETMAR3 ghost beam makes an angle of 5.8 deg with respect to the centerline of the ETM telescope. Internal baffles between the eyepiece lenses, in front of the eyepiece lens #2, and the walls of the telescope barrel in the ETM telescope will trap the ETMAR3 ghost beam and act as a effective beam dump, as shown in figure 40.

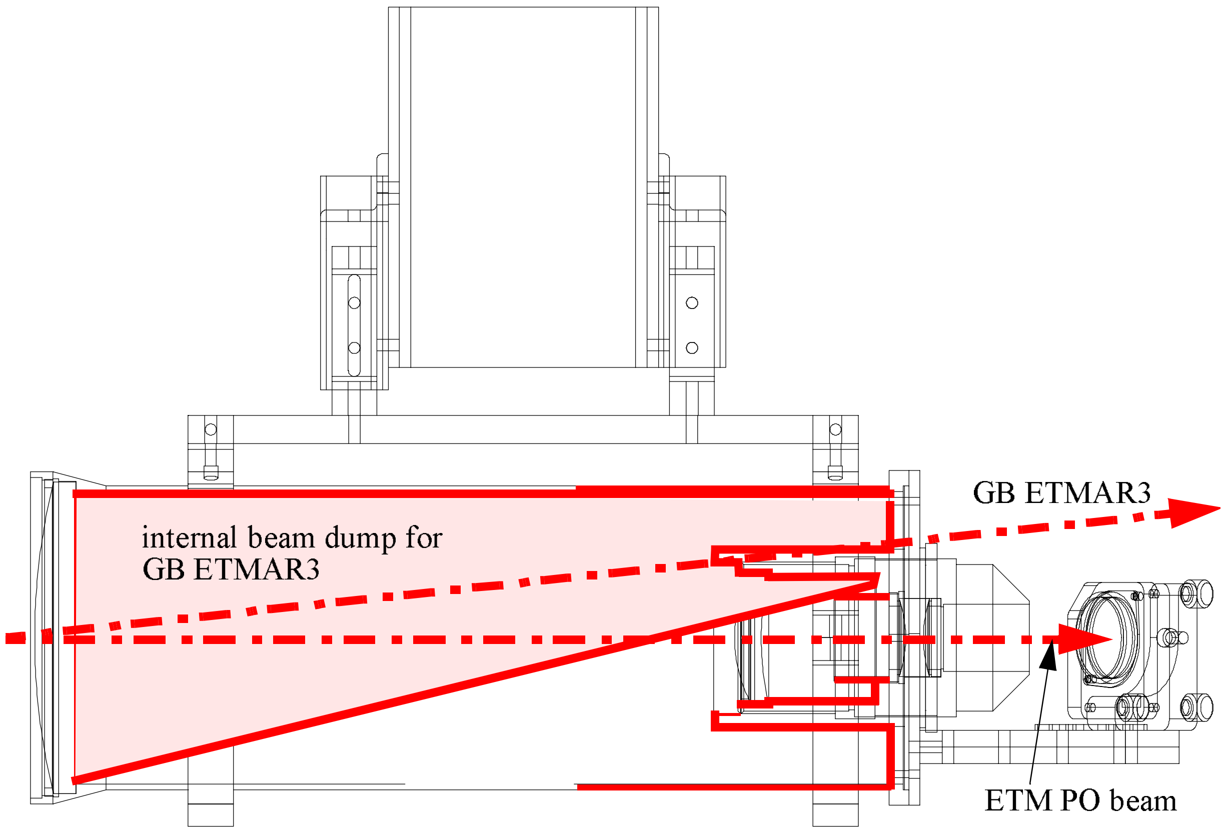

Figure 40: ETM Telescope with internal beam dump

5 OTHER COS ELEMENTS

5.1. Pick-off Mirror

5.1.1. Pick Off Mirror Requirements

Table 12: PO Mirror Requirements

Parameter	*Value*
Size	7.50" +/- 0.01" X 10.5 +/- 0.01 in
Material	fused silica
Thickness	1.00+/- 0.01"

Table 12: PO Mirror Requirements

Parameter	*Value*
Clear Aperture	7.0 X 10.0 inch ellipse
Flatness	1/4 wave @633nm over clear aperture
Surface finish	60/40
Surface roughness	<100 Å
Operating wavelength	1064 nm
Reflectivity coating	>0.99, p polarization, 45 deg incidence
Pitch angle range	+/- 1.5 deg
Yaw angle range	0 - 52 deg

5.1.2. Mounting Height Range Due to COC wedge angle tolerance

The locations of the PO mirrors, and the height range due to the COC wedge angle tolerances are shown in

Table 13: PO Mirror Locations and Height Range

PO Mirror	*PO Mirror Global Coordinates, mm*			*Height below SEI table, mm*	*PO mirror height tolerance, mm*	*PO mirror pitch, deg*	*PO mirror yaw, deg*
	X	*Y*	*Z*				
2K ITMX	9161	8741	257	243	43.6	-2.1	-45.0
2K ITMY	8763	9071	244	256	41.7	-2.0	-45.0
2K BS	9123	384	289	211	42.3	-1.2	88.2
4K ITMX	186	199	207	293	21.4	-3.2	-50.8
4K ITMY	-199	484	198	302	20.6	-2.8	-44.9
4K BS 1	-163	4397	89	411	20.4	0.0	-45.2
4K BS 2	475	4397	111	389	20.4	-1.0	45.0

5.1.3. Pick Off Mirror Design

The PO mirror assembly contains a two-axis flexure mount which provides a fine pitch and yaw angle adjustment of +/- 2 deg. The coarse yaw angle range is provided by rotating the base of the mirror on the SEI optical table before clamping. The height of the mirror is adjustable by means of the slots provided in the vertical support mounting brackets, as shown in figure 41.

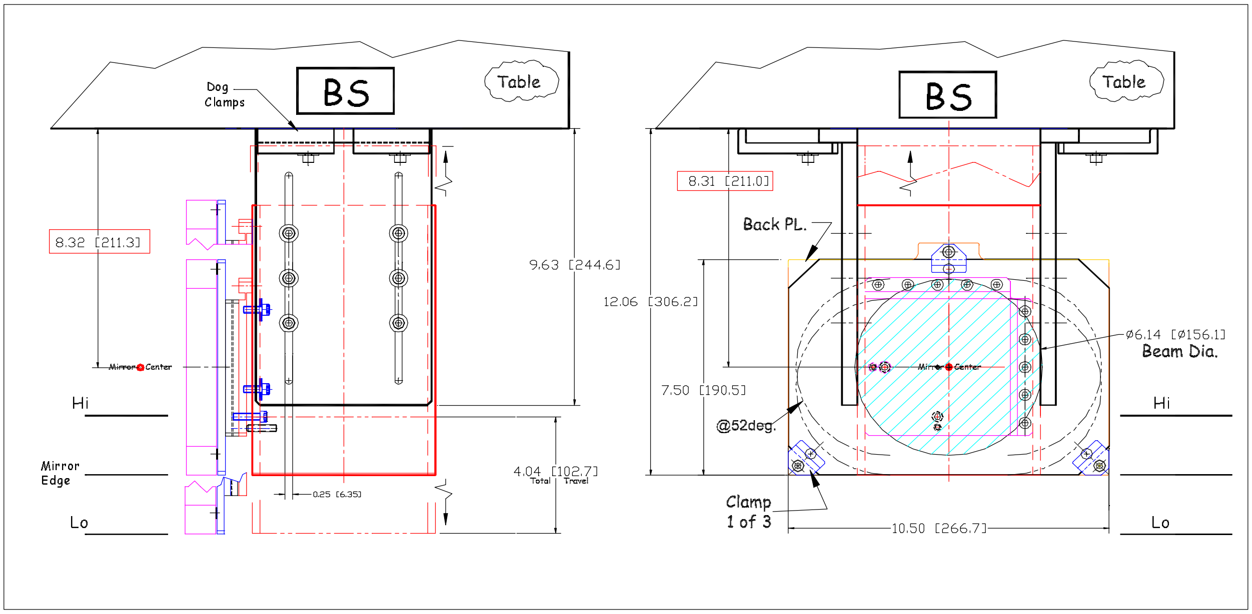

Figure 41: PO mirror mounted to SEI platform

5.2. Faraday Isolator

5.2.1. Faraday Isolator Requirements

Table 14: Faraday Isolator Requirements

Parameter	*Value*
Operating wavelength	1064 nm
Clear aperture	20 mm
Transmissivity across clear aperture	>98.5%
Extinction ratio across clear aperture	$>1\times10^3$
Wavefront distortion	<0.7λ @ 633 nm wavelength

5.2.2. Faraday Isolator Design

5.2.2.1 Return Beam Port Cover

An optical port shall be provided to allow a return beam, which enters the output end, to exit from the polarizer housing. The port shall be covered with a movable cover to block the return beam.

5.2.2.2 Optical Reference Surface

The input side of the mechanical housing shall have a flat, optical reference surface which is perpendicular to the optical axis within <0.5 degrees. A removable mirror will be mounted against the reference surface to retroreflect an autocollimator beam for alignment purposes. The flat reference surface shall have fiducial marks which define the center of the input optical axis within <0.5mm.

5.2.2.3 Polarizer Alignment

The polarization axis of both polarizers shall be rotatable about the optical axis to any angle with respect to the horizontal mounting surface of the Faraday isolator assembly, with an angle reproducibility of <0.5 degree.

5.2.2.4 Polarization Rotation

The half-wave polarization retardation plate shall be rotatable about the optical axis to any angle with respect to the horizontal mounting surface of the Faraday isolator assembly, with an angle reproducibility of <0.5 degree.

5.2.2.5 Materials

5.2.2.5.1 Faraday Rotator Optic

material	TGG crystal.
input and output surface wedges angle	>1 deg,

An antireflection coating shall be applied to both surfaces of the Faraday optic; to be purchased from REO (Research Electro Optics).

Wavelength	1064 nm
Transmissivity per surface	>99.9%
Durability	MIL-C-675C

5.2.2.5.2 Input/output Polarizer

material	optical quality calcite.
surface orientation	Brewster's angle @ 1060nm, all surfaces
wavefront distortion	<1/2 waves, @ 633 nm

5.2.2.5.3 Polarization Rotation Plate

material	quartz
phase retardation	1/2 wave @ 1064 nm
retardation order	zero order

An antireflection coating, to be purchased from REO (Research Electro Optics), shall be applied to all four surfaces of the half-wave plate,.

Wavelength	1064 nm
Transmissivity per surface	>99.9%
Durability	MIL-C-675C

5.2.2.6 Vacuum Compatability

The Faraday isolator assembly is constructed of the standard materials used in EOT Model No. 1845-20, which is similar to the Faraday isolator model that was vacuum qualified by LIGO with an RGA test. In addition the following materials will not be used: organic materials, vacuum grease, adhesives including epoxy, anodizing, lubricants.

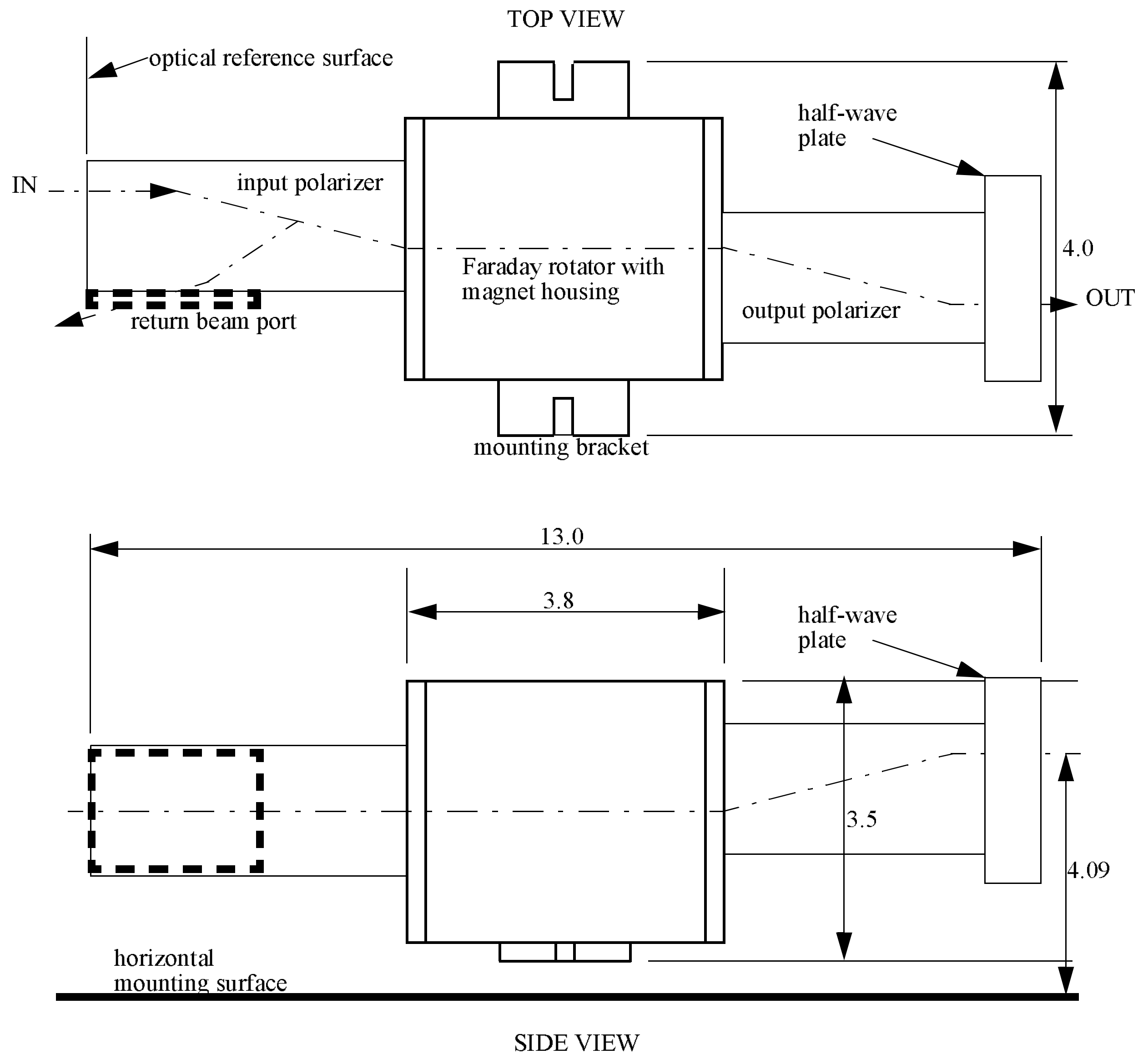

Figure 42: Figure 1: Approximate outline dimensions of Faraday Rotator Assembly

5.3. Steering Mirrors and Periscopes

5.3.1. Steering Mirror Requirement

Table 15: Steering Mirror Requirements

Parameter	*Value*
Diameter	2.00" +/- 0.01" or 50 mm +/-0.25 mm
Material	fused silica
Thickness	0.37"/0.39" +/-0.01"
Clear Aperture	Central 85%
Flatness	1/10 wave @633nm over clear aperture
Surface Roughness	<0.8 Å (Superpolish)
operating wavelength	1064 nm
reflectivity coating #1	0.999, p or s polarization, 0 deg incidence
reflectivity coating #2	0.999, p polarization, 45 deg incidence
reflectivity coating #3	0.999, s polarization, 45 deg incidence

5.3.2. Steering Mirror Design

2 inch diameter steering mirrors and periscopes are used at the output of the PO telescopes to direct the beam down to the output window height, and to direct the beam along the table and out the output window. The mirrors are used at a variety of incidence angles and orientations, which require different high reflectance coating designs to achieve 99.9 % reflectivity.

A common mirror mount is used to hold all of the periscope mirrors and steering mirrors. The mount is a modified three-point commercial kinematic design, and is high-vacuum compatible.

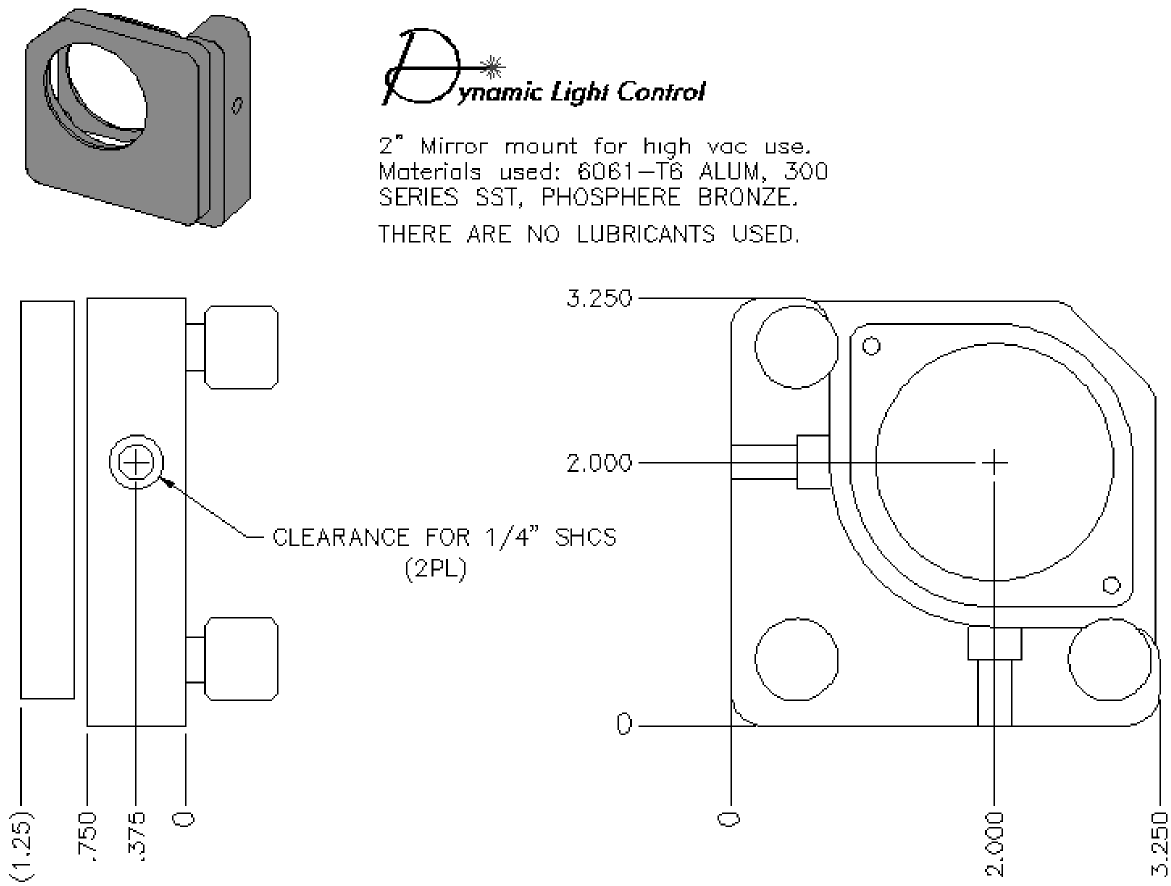

Figure 43: 2 inch steering mirror mount

5.4. Output Window

The output window is used in HAM1 and HAM7 for the IO input laser beam and for the ISC diagnostic beams. The output window is also used for each of the PO beams in the IFO: ITMx, ITMy, BS, APS, ETMx, and ETMy.

5.4.1. Output Window Requirements

Table 16: Output Window Requirements

Parameter	*Value*
Diameter	2.00" +/- 0.01" or 50 mm +/-0.25 mm
Material	fused silica
Thickness	0.500 inches

Table 16: Output Window Requirements

Parameter	*Value*
Clear Aperture	2.75 inches min
Wavefront distortion	<l/10λ @ 633 nm wavelength
Surface Roughness	<100 Å
operating wavelength	1064 nm
Transmissivity	>99.9% at 1060nm and normal incidence
Wedge	30 min. +/- 5 min
Material	Optical grade "A" fused silica

5.4.2. Output Window Design

5.4.2.1 Eccentric Window Design

The optical window is mounted within a modified conflat at an eccentric position. This allows a larger effective aperture coverage by rotating the conflat when it is mounted.

5.4.2.2 Antireflection Coating

5.4.2.2.1 Type 1 (purchase from REO (Research Electro Optics))

Applied to both surfaces of window optic

Protective overcoating	SiO_2 overcoat on outside surface
Polarization	S
Wavelength	1064 nm
Incidence angle	5 deg
Transmissivity per surface	>99.9%
Durability	MIL-C-675C

5.4.2.2.2 Type 2

Applied to both surfaces of window optic

Protective overcoating	SiO_2 overcoat on outside surface
Polarization	S
Wavelength	1064 nm
Incidence angle	5 deg
Transmissivity per surface	>99.6%
Durability	MIL-C-675C

5.4.2.3 Flange Configuration

Standard 10" conflat (see figure 44)

5.4.2.4 Protective cover

An aluminum cover, 0.250” thick and 5.5” diameter shall be provided to protect the exterior surface of the window. A pattern of six #8-32 x 0.500” deep blind holes shall be provided surrounding, and concentric with the off axis window (see figure 44), for attaching the cover. This cover shall be machined flat on one surface, to mount to the stainless steel flange without a gasket, and relieved if necessary, to clear the face of the optical window by >0.040 inch.

5.4.2.5 Windows

Material - Optical grade “A” fused silica (Hereaus Infrasil 301-A, Herasil 1-A, Suprasil 311-A, Suprasil 312-A)
A substitution of any other window material must be approved by cognizant LIGO personnel.

5.4.2.6 Window assembly

bellows seal	braze alloy to be 97.5% lead, 2.5% silver alloy
Edging	edge chips shall not exceed 10% of the total perimeter, or be larger than 0.03" max width.
Location	center of optical window to be placed 0.95 inches from the center of the conflat flange (see figure 44).

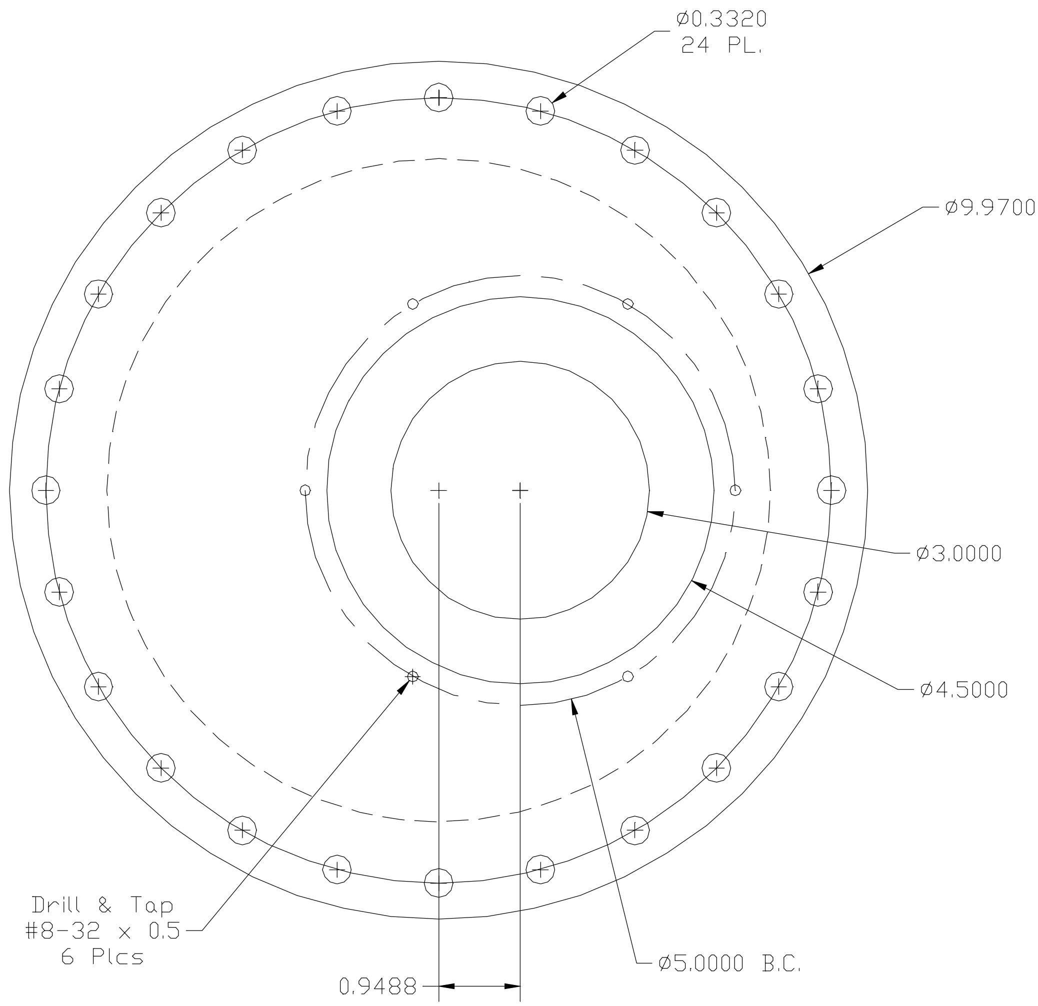

Figure 44: Output window mechanical layout

6 ALIGNMENT PROCEDURE

An IR alignment telescope/autocollimator with a 940 nm wavelength illumination source will be used to establish the locations of the beam-dumps, baffles, PO mirrors, and PO telescopes in the IFO; and to align the optical axes of the PO telescopes. The autocollimator mode will be used for setting the COS alignment beam parallel to the IFO optical axis, and for aligning the optical axes of the PO telescopes. The alignment telescope mode will be used to project a focussed reticle alignment mark for centering the alignment beam, beam-dumps, baffles, PO mirrors, and PO telescopes.

6.1. IR Alignment Beam

The IR autocollimator/alignment telescope will be placed on the SEI platform in HAM3 to provide an alignment beam for the 4K and 2K IFO, as shown in figures 45 and 46. First the alignment telescope will be focussed to project an image of the reticle onto a target centered on the ITM_x.

.

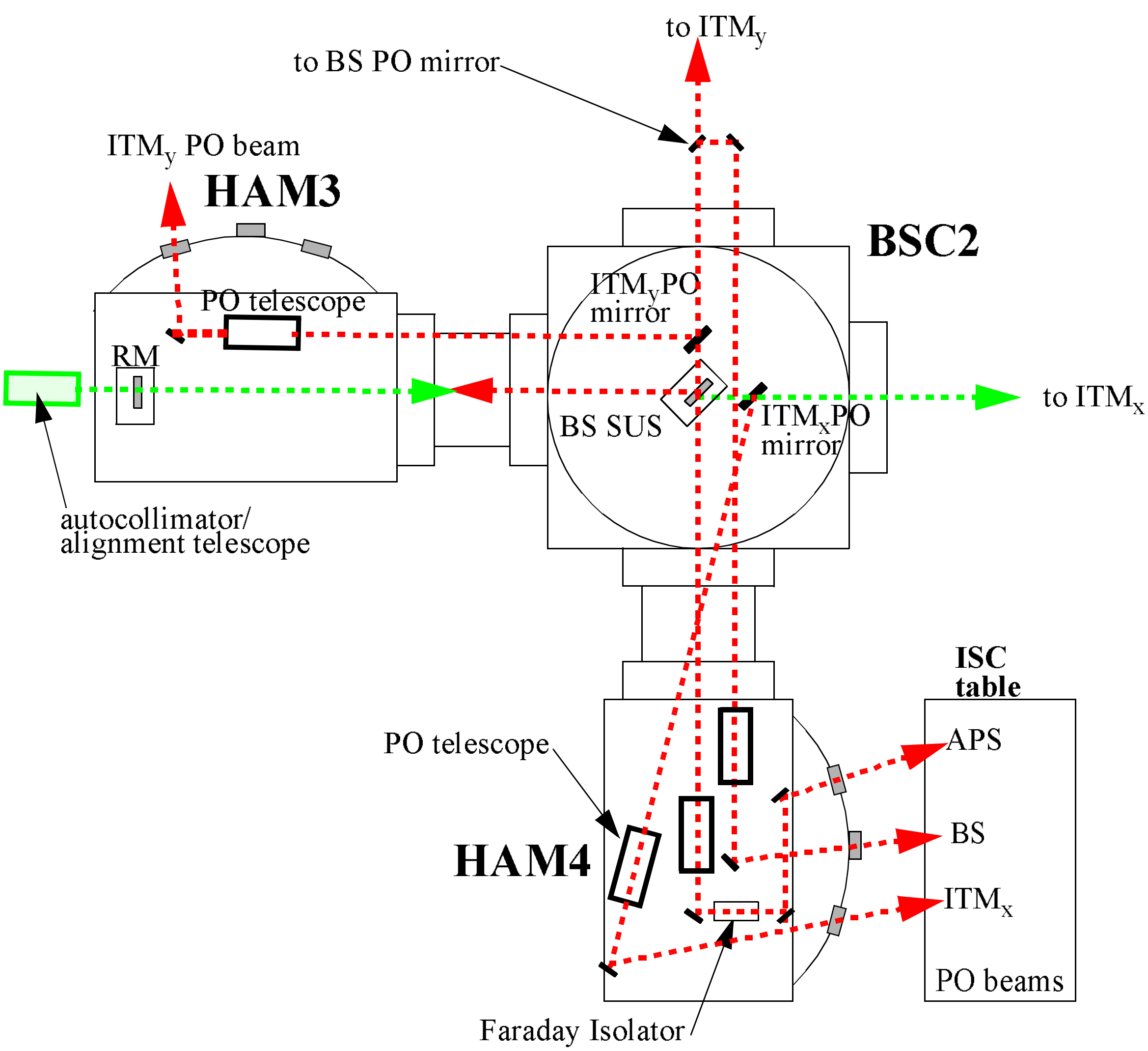

Figure 45: Alignment Beams for COS, 4K IFO

Next the autocollimator will be focussed at infinity and adjusted in pointing angle so that the reflected reticle image is nulled, making the beam perpendicular to the ITM_x. Finally the tilt and displacement of the autocollimator will be iteratively adjusted until the alignment beam is both centered and perpendicular to the ITM_x. The same procedure will be used in the 2K IFO, as shown in figure 46.

The power in the various alignment beams is shown in Table 17 on page 63.

Table 17: Alignment Beam Power

Beam	*location*	*Power @ 940nm*
alignment x, retro	HAM4	1.32E-04
alignment y, retro	HAM4	1.68E-04
APSxPO beam	HAM4	1.65E-04
APSxTEL out	HAM4	1.37E-05
APSxTEL, align	HAM4	**4.47E-06**
APSx PO ISC	output window	2.53E-03
ITMx PO beam	HAM4	3.33E-04
ITMx TEL out	HAM4	2.76E-05
ITMx TEL, align	HAM4	**9.03E-06**
ITMx PO ISC	output window	3.93E-03
BS PO beam	HAM4	8.22E-06
BS PO TEL out	HAM4	6.82E-07
BS TEL, align	HAM4	**2.23E-07**
BS PO ISC	output window	3.89E-03
GBITMxAR1	beam dump BSC2	1.38E-04
GBITMxAR4	beam dump BSC2	3.43E-05
GBITMxHR3	beam dump BSC7	2.75E-05
GBITMxHR4	beam dump BSC7	2.81E-06
GBBSAR3x	beam dump BSC3	8.13E-06
GBBSHR3y	beam dump BSC1	1.63E-07
GBBSAR1y'	beam dump HAM4	6.72E-06
GBBSAR3y'	beam dump HAM4	1.65E-04
GBBSHR3x'	beam dump HAM4	1.65E-06
GBITMyAR1	beam dump BSC2	1.41E-04
GBITMyAR4	beam dump BSC2	3.50E-05
GBITMyHR3	beam dump BSC8	2.81E-05
GBITMyHR4	beam dump BSC8	2.87E-06

.

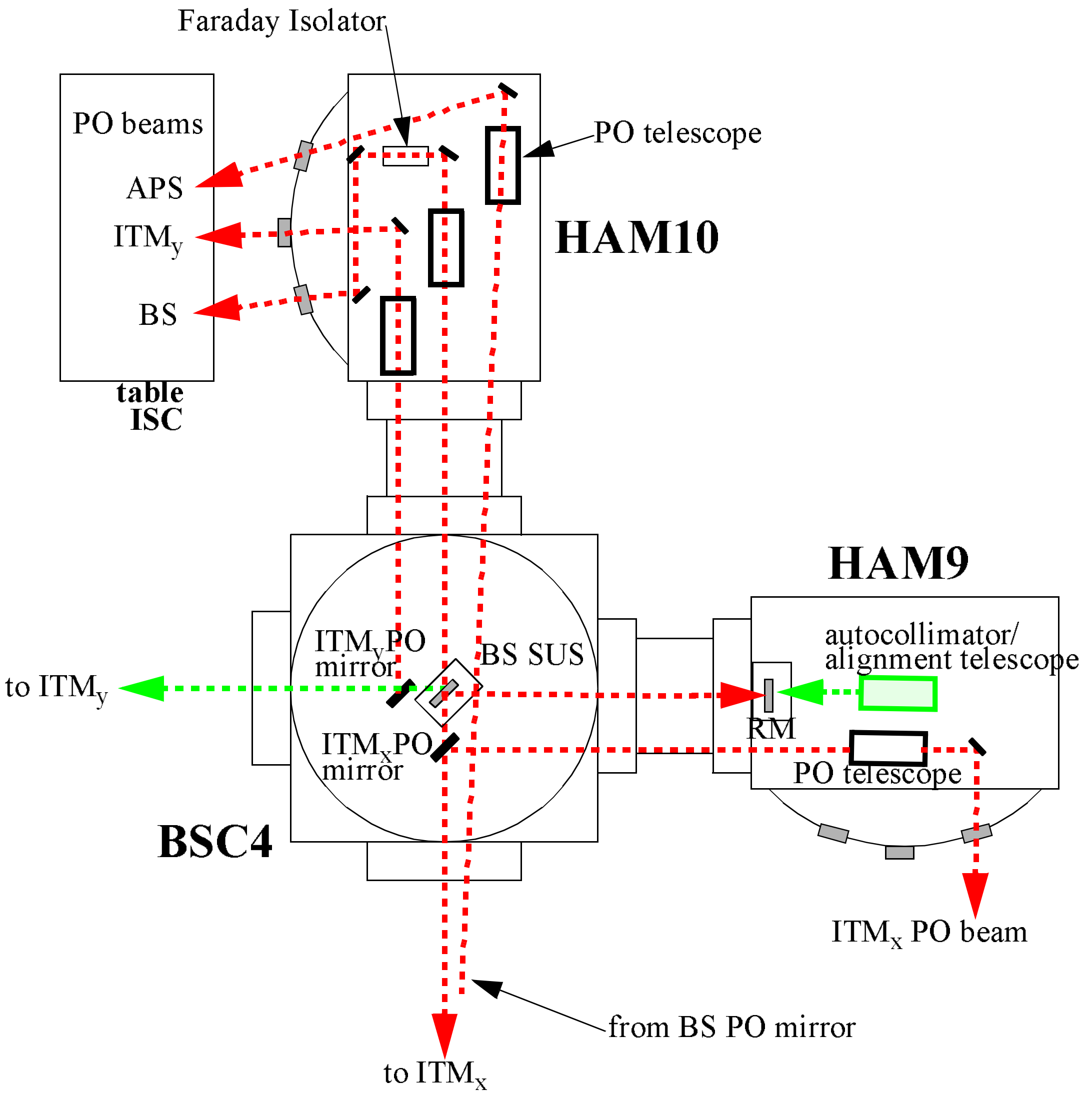

Figure 46: Alignment Beams for COS, 2K IFO

6.2. Positioning of COS Optical Elements

Ghost alignment beams will be generated by the wedge surfaces of each COC. Each COS optical element, e.g. the PO mirrors, beam-dumps, etc., will be positioned by focussing the alignment telescope and projecting a ghost reticle onto a temporary target centered on each optical element; then by moving the element until the target is centered on the projected reticle. The alignment telescope has a sufficient focus range, and the beam remains centered with the mechanical axis over the entire focus range.

6.3. Alignment Beam Accuracy

A test of the reticle projection technique was performed with the apparatus shown schematically in figure 47.

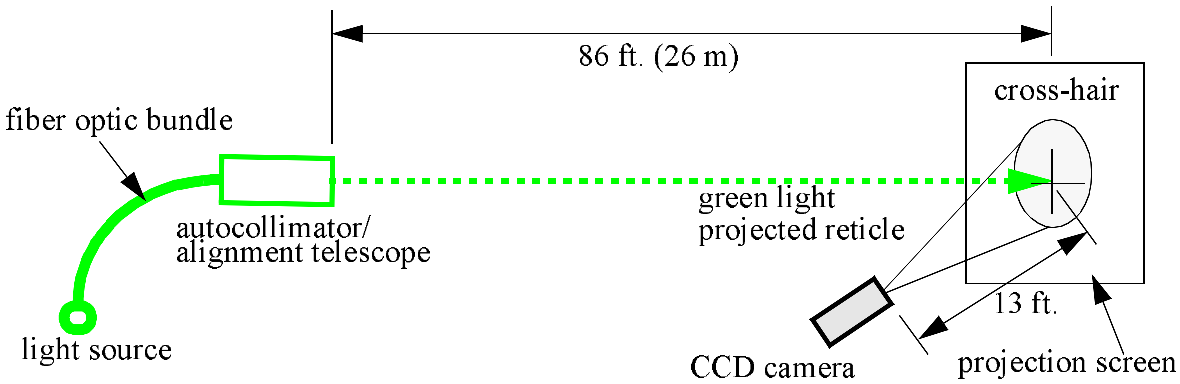

Figure 47: Apparatus to test the projected reticle technique

An image of the projection screen--containing a marked cross-hair, a calibrated machinists scale, and the green light projected image of the reticle from the alignment telescope--was captured with the CCD camera. The marks on the reticle are spaced 1 arc min, and the numbers on the scale indicate inches. The CCD camera image is shown in figure 48.

The observed resolution of the edges of the projected reticle was < 0.010 inch, which is equivalent to an angular resolution of $< 10\times10^{-6}$ rad. The resolution of the reticle image was limited by the pixilation of the CCD camera, which can easily be improved almost an order of magnitude simply by moving the camera closer to the screen. The diffraction limit of the 0.9 inch output aperture of the alignment telescope with 1060 nm light is approximately 10×10^{-8} rad. This implies that the limiting resolution of the reticle image is $< 1\times10^{-4}$ inch at the 26 m distance of the projection screen, and the pointing accuracy of autocollimator is limited to $< 10\times10^{-8}$ rad.

The experiment proved that the reticle projection technique can be used to align a target with a cross-hair to a fraction of a millimeter, and the autocollimator can be pointed to an accuracy of approx 1×10^{-6} rad.

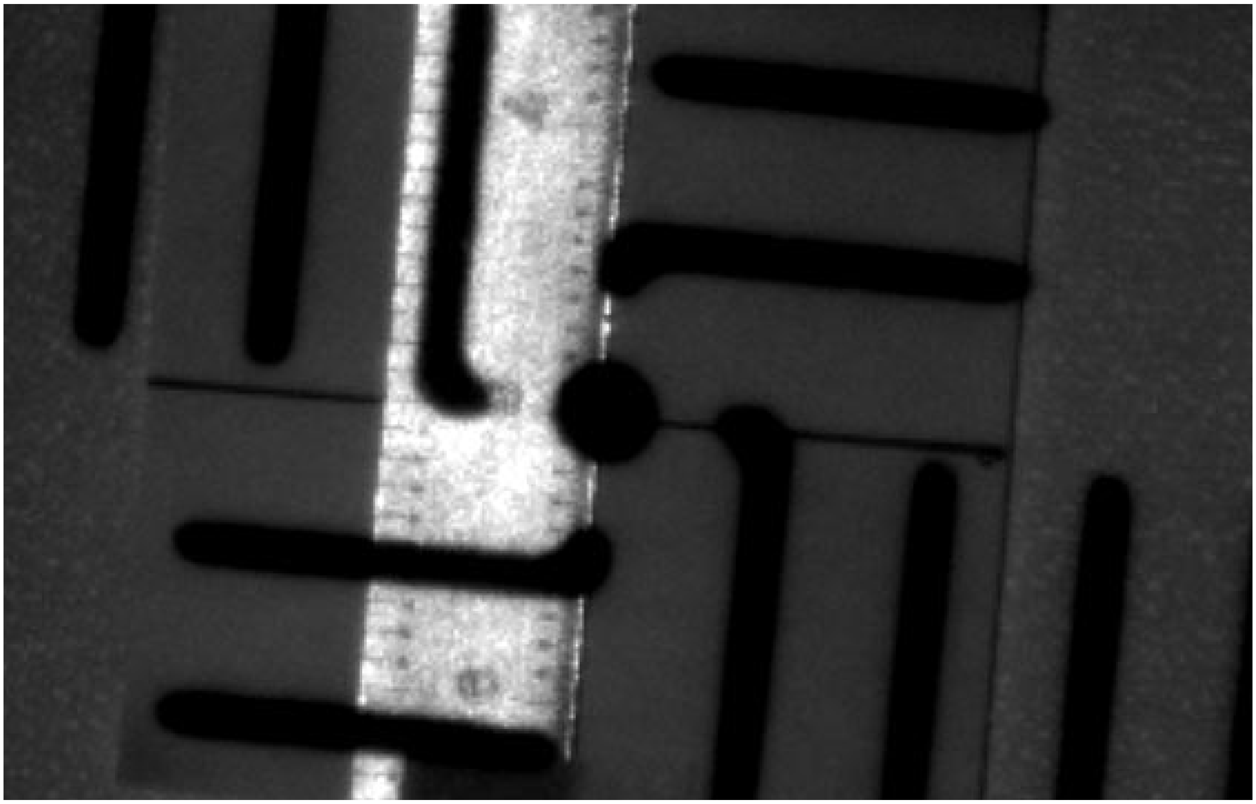

Figure 48: CCD image of the projection screen cross-hair with scale and projected reticle from the alignment telescope

6.4. Alignment of PO Telescope

The autocollimator mode will be used for the pre-alignment of the PO telescopes as well as for the final alignment and pointing on-site in the IFO.

6.4.1. Bench Alignment of PO Telescope

The bench alignment of the PO telescopes will proceed in four steps.

6.4.1.1 Alignment of PO Telescope Housing

Step one is to remove the primary mirror with its mount and to set up the autocollimator perpendicular to the reference surface of the telescope housing by reflecting from the retro-mirror placed against the reference surface of the telescope, as shown in figure 49. Once this has been done, the telescope housing and the autocollimator will be locked down and will remain in fixed positions during the next two steps.

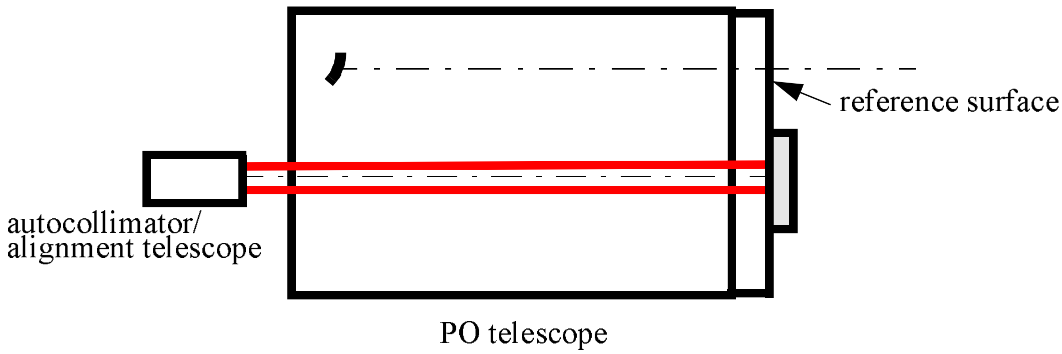

Figure 49: Step one, alignment of PO telescope housing

6.4.1.2 Preset Tilt Alignment of Secondary Mirror Mount

The tilt alignment of the secondary mirror mount will be preset, by placing a first surface mirror against the mirror mounting surface of the secondary mirror mount mirror holder. The secondary mount tilt will be adjusted until the reflected beam is autocollimated, as shown in figure 50. The final adjustment of the secondary mirror will be translation only.

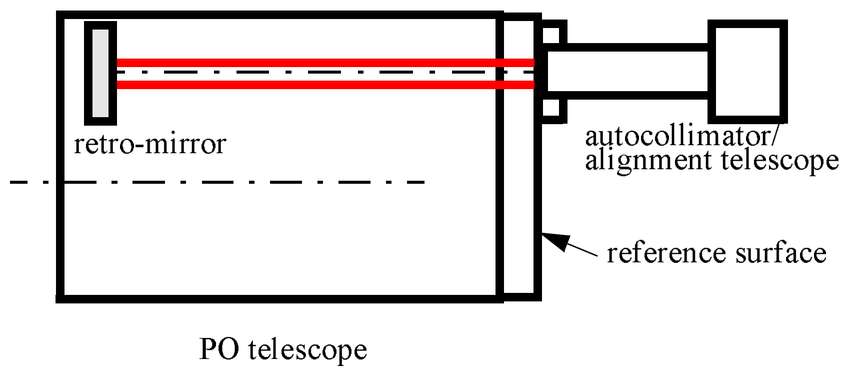

Figure 50: Preset tilt alignment of secondary mirror mount

6.4.1.3 Alignment of Optical Axis of PO Telescope

The second step, as shown in figure 51, consists of installing the primary mirror, placing the small retro-mirror against the reference surface at the output aperture of the telescope, and adjusting the secondary mirror lateral position to bring the output beam perpendicular to the retro-mirror with an approximately plane wavefront. The perpendicularity is determined by nulling the displacement of the return image of the reticle as seen through the autocollimator eyepiece. The flatness of the wavefront is determined by sharpening the focus of the return image with the secondary mirror as much as possible.

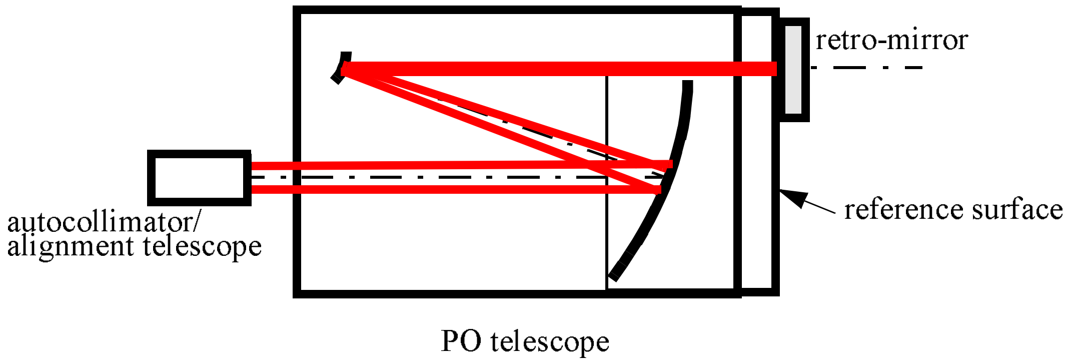

Figure 51: Step two, alignment of PO telescope optical axis

6.4.1.4 Centering of PO Telescope Output Aperture

After the optical axis has been established in step two above, the output flange will be mounted to the reference surface and the alignment telescope will project a focussed alignment cross hair onto the target on the flange for centering with the optical axis of the PO telescope, as shown in figure 52.

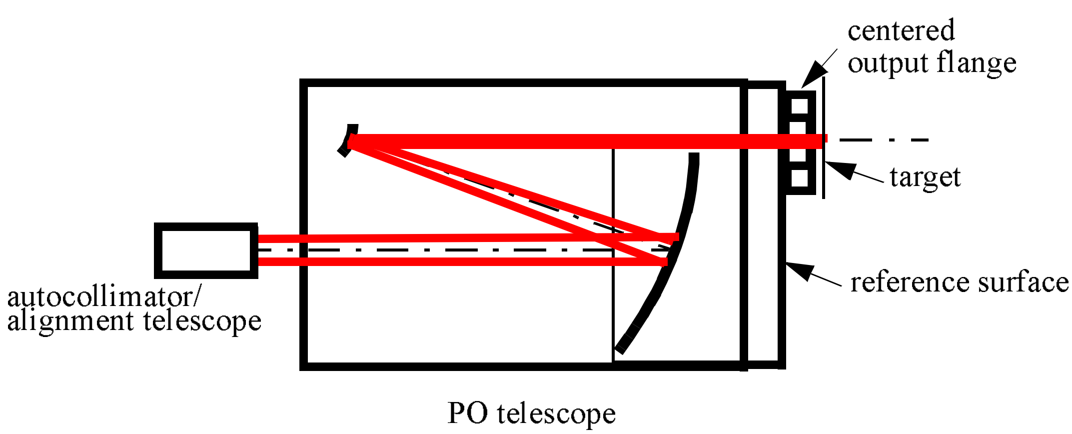

Figure 52: Step three, centering of the output flange with the optical axis

A drawing of the alignment telescope, which will be mounted in the flange at the back of the PO telescope, is shown in figure 53. The flange orients the alignment telescope perpendicular to the optical reference surface for the PO telescope. The flange will be centered with the output beam of the PO telescope by using the projected reticle technique described previously.

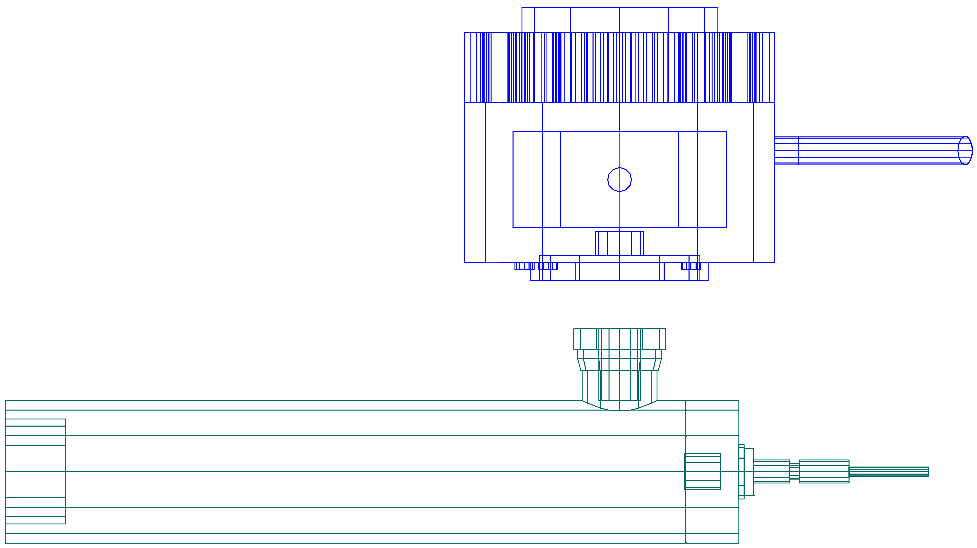

Figure 53: Alignment telescope with IR CCD camera viewer

6.4.1.5 Full Aperture Alignment of PO Telescope

For the final step four, as shown in figure 54, the autocollimator will be moved to the output side of the telescope so as to fill the aperture of the telescope. The barrel of the autocollimator will be inserted into the pre-aligned output flange, which is perpendicular and on-axis with the reference surface. The large retro-mirror will be independently aligned perpendicular the autocollimator. Then, while maintaining the alignment of the telescope by nulling the autocollimator, the secondary mirror lateral translation and focus will be fine-adjusted to achieve the best focussed image of the reticle as seen through the eyepiece of the autocollimator.

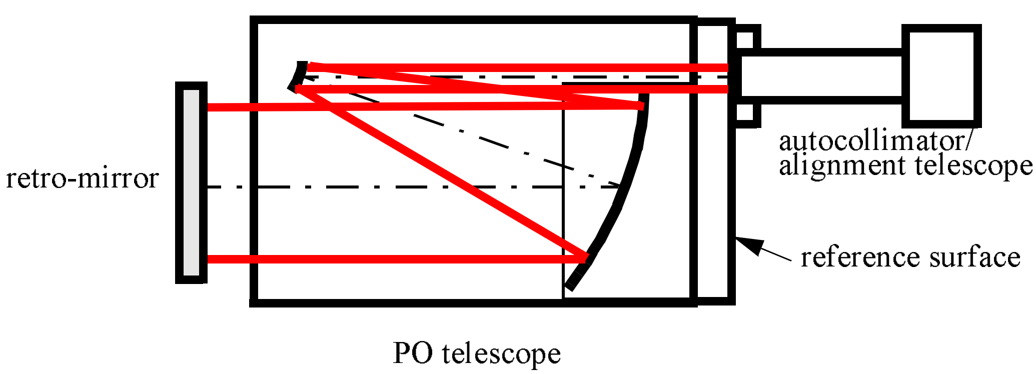

Figure 54: Step four, full aperture alignment of PO telescope

6.4.2. On-site Alignment of the PO Telescope in the IFO

The pre-aligned PO telescope will be centered on the alignment beam by focussing the alignment telescope and projecting a cross-hair onto the entrance aperture of the PO telescope. Subsequently, the PO telescope will be pointed along the axis of the alignment beam by using the autocollimating mode. Refer to figures 45, and 46.

6.4.2.1 Centering Alignment

The center of the primary mirror will be aligned with the axis of the alignment beam by moving the primary gimbal mount until the temporary alignment target placed near the primary mirror is centered on the focussed projected cross-hair image. Next, the entrance-end of the PO telescope will be aligned similarly by moving it until the temporary alignment target placed at the entrance-end of the telescope housing is centered on the projected cross-hair image. Then the primary gimbal mount is locked in place in the middle of its pitch and yaw adjustment range. Any further tilting of the telescope will pivot about the center of the primary mirror, maintaining the centering within the clear aperture.

6.4.2.2 Pointing Alignment

The alignment beam will be focussed at infinity. A second alignment telescope with a pre-centered reticle will be inserted into the output flange of the PO telescope, and the front end of the PO telescope will be tilted in pitch and yaw until the projected cross-hair image is nulled with the reticle of the alignment telescope, as shown in figure 55. The PO telescope is now completely aligned with the reference beam.

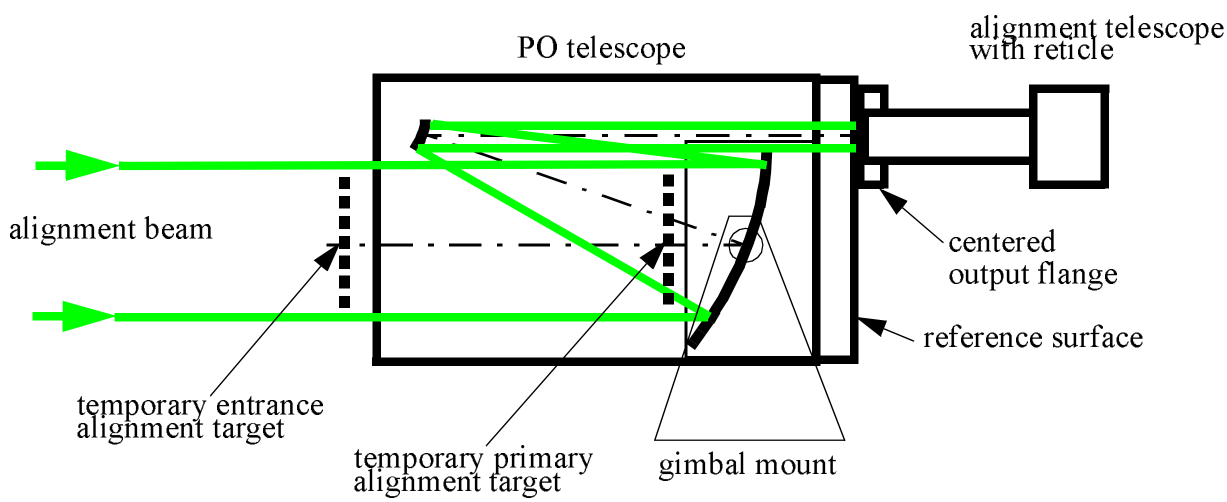

Figure 55: On-site alignment of PO telescope in the IFO

6.5. Alignment of ETM Telescope

The autocollimator mode will be used for the pre-alignment of the ETM telescopes as well as for the final alignment and pointing on-site in the IFO.

6.5.1. Bench Pre-alignment of ETM Telescope

The ETM telescope mechanical tolerances and optical fabrication tolerances of the elements will ensure that the only alignment required is the focus adjustment.

6.5.1.1 Autocollimating through the ETM Telescope

The assembled ETM telescope will autocollimated by inserting the alignment telescope/autocollimator into the cylindrical bore at the small end of the ETM telescope and projecting the cross hair of the autocollimator out through the large diameter of the ETM telescope.

Next, a mirror will be placed at the large end of the ETM telescope and tilted until the retroreflected cross hair is aligned with the autocollimator reticle.

6.5.1.2 Focus Adjustment of ETM Telescope

The final step is to move the two eyepiece lenses as a group until the best focus is obtained with the autocollimator. This ensures that the ETM telescope is in the best afocal alignment.

6.5.2. On-site Alignment of ETM Telescope

The ETM telescope will be aligned on-site by placing an autocollimator on the SEI platform and autocollimating from the HR surface of the ETM mirror, as shown in figure 56. The autocollimator beam will transmit through the ETM and will enter the ETM telescope. A second autocollimator placed in the cylindrical bore at the output of the telescope will receive an image of the projected cross hair.

First, a concentric target will be placed at the entrance pupil of the ETM telescope and the autocollimator will be used in alignment telescope mode to project a cross hair onto the target. The ETM telescope will be moved transversely to align the target with the cross hair.

Finally, the ETM telescope will be tilted in pitch and yaw until the projected cross hair from the input autocollimator aligns with the reticle of the output autocollimator.

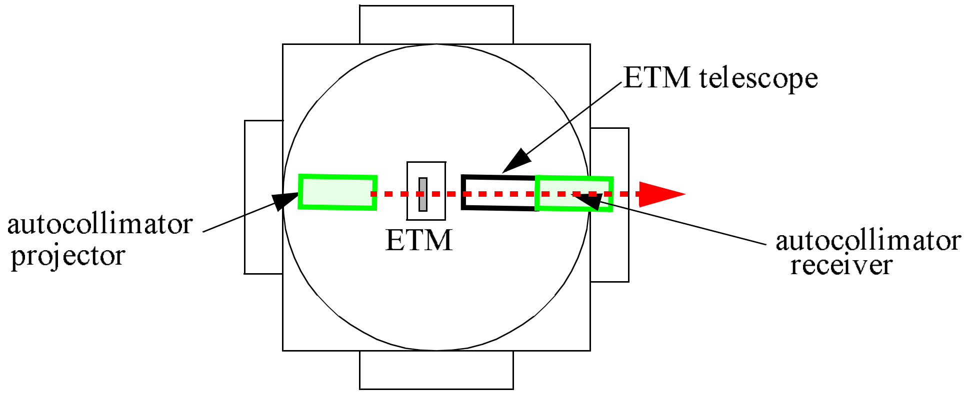

Figure 56: On-site alignment of ETM telescope