LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T070076-02 | Advanced LIGO | 5 April 2008

Optical Layout for Advanced LIGO

Advanced LIGO Systems Group, Dennis Coyne (ed.)

Distribution of this document:
Advanced LIGO development team

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

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

1 Introduction

The advanced LIGO optical system is comprised of the following primary elements:

(1) the Input & Output Optics (IO), which consist of the modulation, input mode cleaning and input mode matching optics[1];

(2) the Core Optics Components (COC), which consist of the suspended optics which form the Power recycling Cavity (PRC), the Signal Recycling Cavity (SRC) and the Fabry-Perot (FP) arm cavities,

(3) the Auxiliary Optics Subsystem (AOS), which consist of the stray light control, recycling cavity pick-off beam sampling, optical levers, Thermal Compensation System (TCS) and

(4) the Output Optics (OO) [handled by the ISC group], which consist of the output mode cleaning and detection optics.

The purpose of this document is to define the fundamental requirements, constraints and design approach for the optical layout. The optical layout details are documented in a companion document[2], T080078. Most of the key parameters for the layouts (cavity lengths, optic dimensions, etc.) are documented in separate source documents which are cited in this document.

The overall layout is coordinated with the involved subsystems, through integrated optomechanical layout models which are the responsibility of the systems group. The layout is the result of collaboration between the AOS, IO, ISC, COC, SUS, SEI and Systems groups.

2 Scope

The scope of this document is the in-vacuum optical layout with the exception (at the time of this preliminary design review) the HAM1/7 and HAM6/12 chambers. These chambers are the ISC chambers used for in-vacuum detection. The layouts for the PSL/IO & ISC exo-vacuum tables are currently handled by these groups separately (and not part of the integrated layout).

3 Coordinate System

The LIGO global coordinate system[3] is defined with its coordinate axes aligned along the center of the BTs and its vertex at the projected intersection of these axes. The heights of the chambers and

[1] Note that in the stable recycling cavity design which has been baselined, the IO group and the COC group collaborate on the mode matching telescope elements which are part of the recycling cavities; See RODA M080038-03 for details.

[2] M. Smith, D. Coyne, Stable Recycling Cavity Mirror Coordinates and Recycling Cavity Lengths, LIGO-T080078-02

[3] A. Lazzarini, Determination of Local and Global Coordinate Axes for the LIGO Site, LIGO-T980044-10, 7 Feb 2001
A. Lazzarini, Determination of the as-built LIGO Global Coordinate Axes for Hanford, WA: Final analysis of the LIGO BT/VE interface survey monuments", LIGO-T960176-C, 26 Nov. 96.; This supersedes "Orientation of the Beam Tube Enclosure Foundation with Respect to the Local Horizontal: Hanford Site, LIGO-D950140-A, 28/11/95, which needs to be revised.

the SEI optics tables are adjusted so as to be locally level but at the proper position relative to the projected BT axes at their centers.

The optical ray tracing is done in a shifted coordinate system in which the center of the splitting surface of the unfolded interferometer BS is defined as the origin. Positions of the optical components are then transformed (shifted) to the LIGO global coordinate system, unless otherwise noted. The positions and orientations of the optics at each observatory are then determined by transforming into the local horizontal coordinate systems in each building.

4 Requirements

4.1 Non-Folded Interferometer Commonality

The non-folded interferometers, designated H1 at LHO and L1 at LLO, are common in their design and implementation. We do not propose to implement unique designs, realizations or placement of equipment that can be accommodated for L1 due to the lack of presence of an L2.

4.2 Layout Topology

The folded (H2) and non-folded (H1) interferometers share the same beam tube aperture, by being displaced horizontally relative to the vertical centerline. The heights are set to be the same in the Fabry- Perot cavities and in the input optics section for commonality of seismic isolation table heights and suspension structure lengths. The basic topology of the vacuum system and optical layout is depicted in Figure 1.

The current (Initial LIGO) vacuum equipment geometry[4] will be revised for the following reasons:

- The H2 interferometer will be lengthened from 2 km to 4km
- HAM Chamber Relocation: For the H1 and L1 interferometers, the HAM2 and HAM5 chambers will be relocated so that they can be used for in-vacuum detection optics; similarly for the H2 interferometer, the HAM8 and HAM11 chambers will be relocated. The Mode Cleaner (MC) cavity length is such that it spans the distance between the HAM1 and HAM3 chambers (in the current system), leaving HAM2 and HAM5 (or HAM8 and HAM11 for H2) available. Relocation of these chambers permits us to change their vacuum state independently from the main vacuum system. The benefit is that the detection sensors and optics can be adjusted and revised without the penalty of a complete system vent and pump-down. (Note that the vacuum septum plates employed in Enhanced LIGO, between the current output manifold tube and HAM6, may not be used for Adv. LIGO; the locations of the viewports in this septum plate are not considered a constraint in the layout.)
- Due to the wider (triple) MC suspensions (relative to Initial LIGO) and the larger diameter Advanced LIGO beam, the diameter of the input and output section manifold tubes are too small. In addition, to improve visibility of the input and output sections for optical levers

[4] The LIGO vacuum equipment layout is defined in the following drawings: For the Hanford Observatory: D961165, D961168, D961169, D961170 and D961171. For the Livingston Observatory: D970383, D970384 and D970385. NEW DRAWING NUMBERS!!

and cameras (a problem/limitation for Initial LIGO), we plan to incorporate many viewports into the new larger diameter manifold tubes.

Note that the HAM chambers are re-numbered for Advanced LIGO, based on their position (sequentially) and not based on their original Initial LIGO number. The (re)naming convention for the HAM and BSC chambers is also indicated in the Figure.

The vacuum system revisions are covered in the scope of the Facility and Modifications and Preparations (FMP) subsystem.

4.3 Stable Recycling Cavities

Both the power and the signal recycling cavities are stable designs[5] as required in the Advanced LIGO Systems Design document, T010075-01, section 3.10.

The recycling cavity lengths are defined by the Interferometer Sensing and Control (ISC) subsystem; see the ISC Conceptual Design Document (CDD), T070247-00, Table 2 and section 2.2.4.

The Schnupp asymmetry is also defined in the ISC CDD, T070247-00; see Table 2 and section 2.2.3.

The nomenclature for the optical elements of the recycling cavities is defined in Figure 2 (and RODA M080038-03)

[5] Note that previous versions of this document, as well as T060153-00, were explicitly for marginally stable power and signal recycling cavities.

Figure 1: Advanced LIGO Vacuum Envelope (New layout overlaid on existing layout)

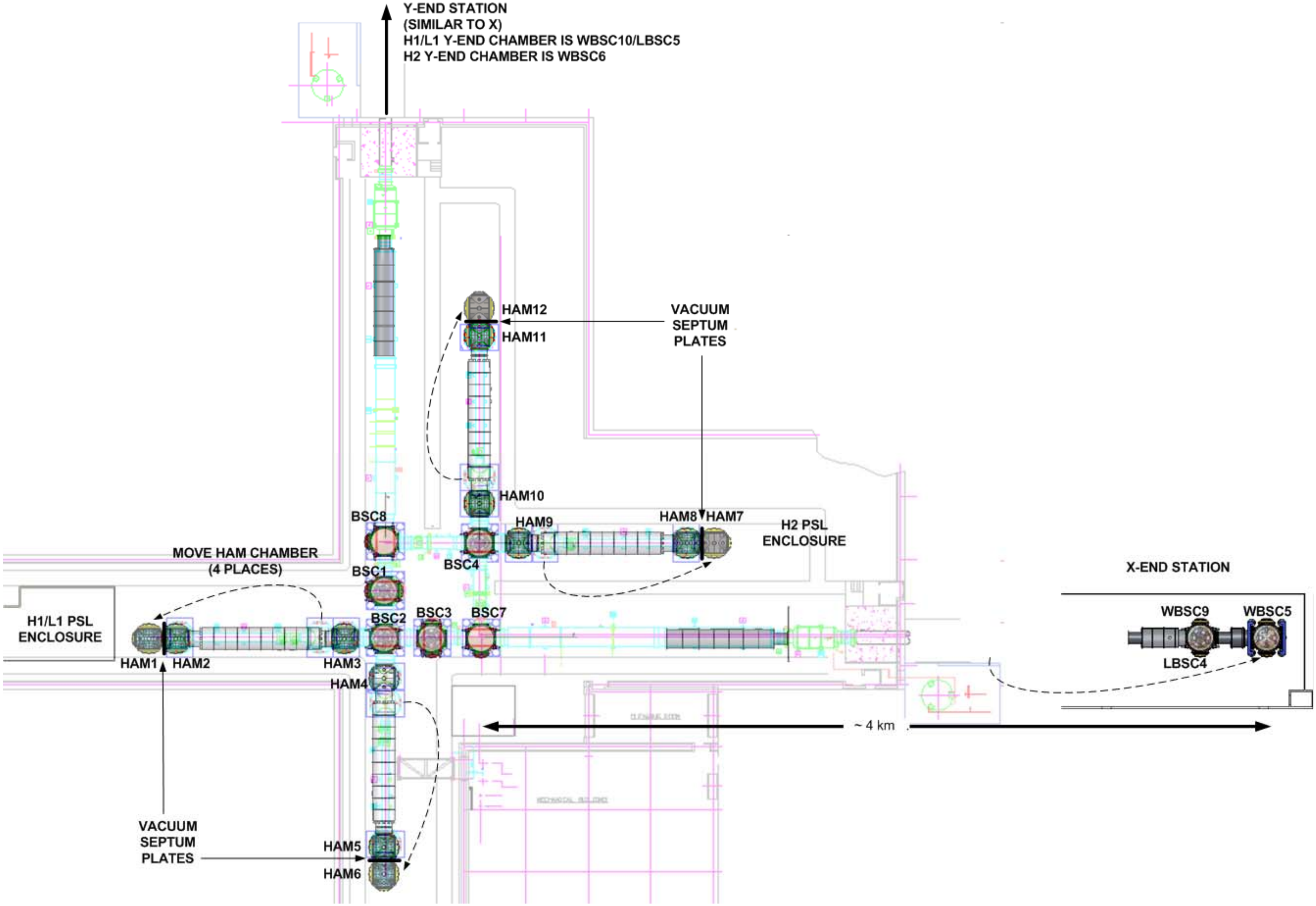
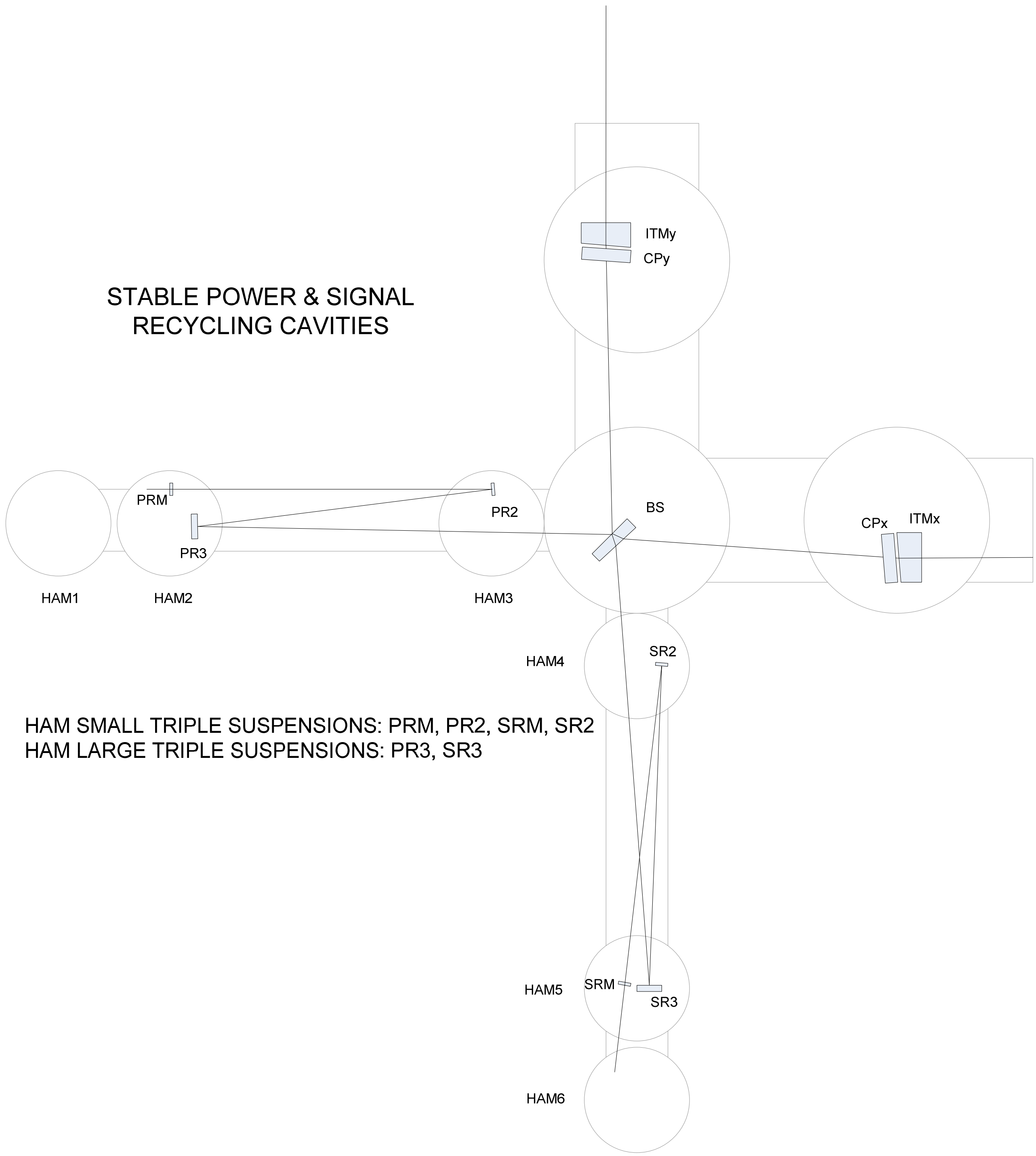


Figure 2: Stable Power and Signal Recycling Cavity Nomenclature & Geometry



4.4 Interferometer Optical Signal Beams

The optical layout must accommodate the following optical signals[6,7,8] (shown schematically in Figure 3):

- Laser injection beam
- PSL intensity stabilization beam
- IMC length and alignment sensing beam
- Reflected port signal
- Recycling Cavity pick-off beams
- Antisymmetric port, or gravitational wave, readout
- ETM transmitted beams

The layout requirements for each of these optical beams are discussed in the following subsections.

4.4.1 Laser Injection Beam

The IO group applies phase modulation, mode matches the beam to the mode cleaner, and applies power control before delivering the beam for injection into the vacuum system. The laser injection beam is needed in the HAM2 chamber.

4.4.2 PSL intensity stabilization beam

Provision must be made to sample the laser light after the Input Mode Cleaner (IMC) for use in an outer intensity stabilization loop for the Pre-Stabilized Laser (PSL). This beam should be delivered to HAM1/7 for use with an in-vacuum photodiode.

4.4.3 IMC length and alignment sensing beam

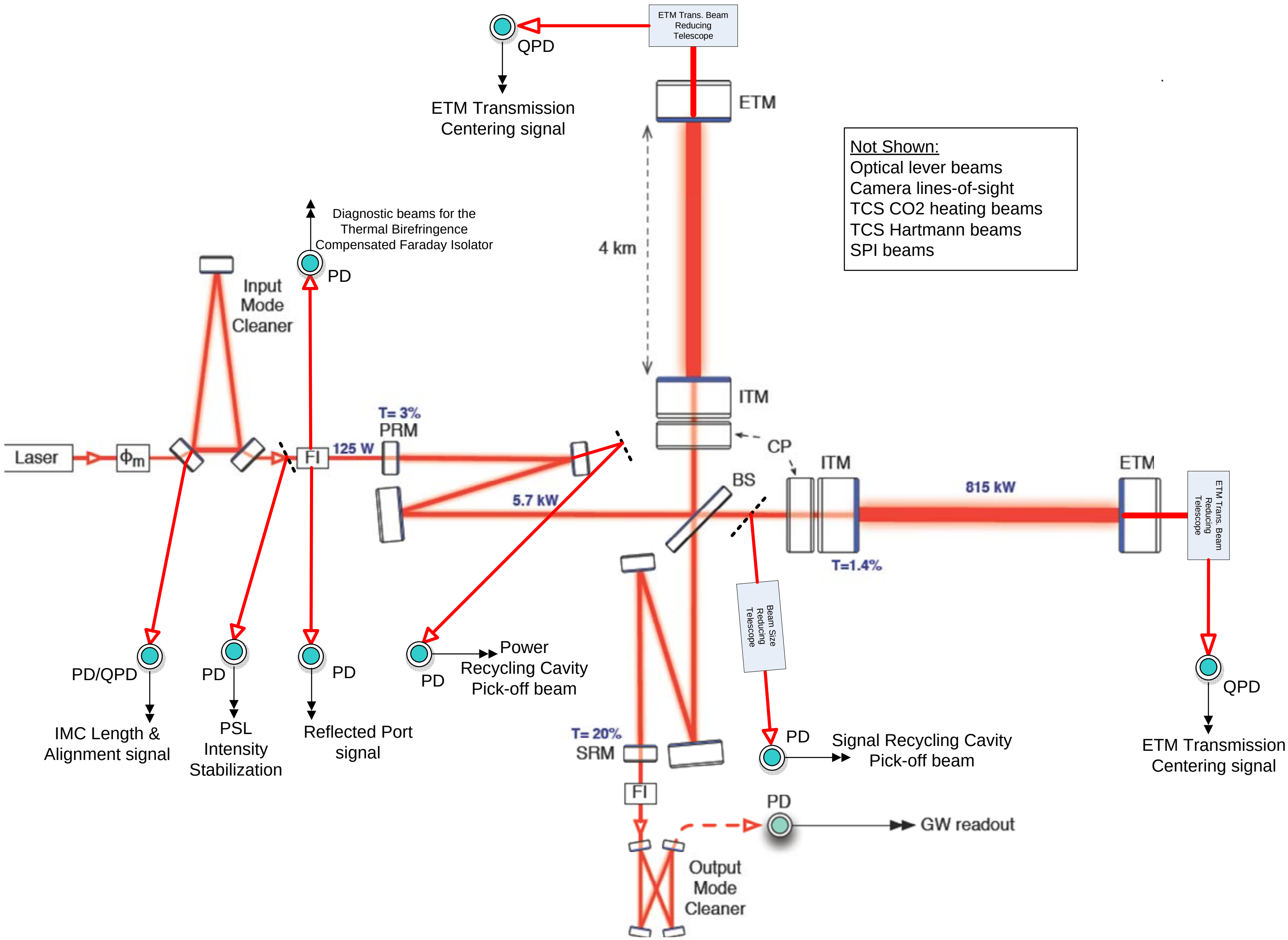
The reflected beam from the Input Mode Cleaner (IMC) must be routed to the HAM1/7 chamber for use by ISC in controlling the length and alignment of the mode cleaner.

[6] M. Arain, et. al., Input Optics Subsystem Preliminary Design Document, LIGO-T060269-02, sections 3.1.1.2, 3.3.1.2, 4.2.2

[7] M. Frede, et. al., Advanced LIGO Pre-stabilized Laser Conceptual Design Document, LIGO-T050035-02, section 2.6

[8] R. Abbott, et. al., AdvLIGO Interferometer Sensing and Control Conceptual Design, LIGO-T070247-00, section 1.4

Figure 3: Interferometer Optical Signals



4.4.4 Reflected port signal

The interferometer symmetric (reflected) port beam is routed to HAM1/7 for use by ISC in length and alignment control. This back-reflected beam is provided by the exit polarizer of the IO FI assembly.

4.4.5 Recycling Cavity pick-off beams

Light samples (pick-off beams) from the Power and Signal Recycling Cavities (PRC and SRC) are needed for length and alignment control by ISC. A pick-off beam from the PRC (named POP) is delivered to HAM1/7. A pick-off beam derived from ITMx (named POX) is delivered to HAM6/12.

4.4.6 Gravitational wave readout signal

The main beam transmitted through the SRM (the antisymmetric port, or gravitational wave, readout named AS) is routed to the Output Mode Cleaner (OMC) suspension in HAM6/12.

4.4.7 ETM transmitted beams

The Fabry-Perot arm cavity light transmitted through the ETM and the ETM reaction mass is reduced in diameter and delivered to an in-vacuum quadrant photodiode for beam centering control by ISC. These optical signals are named PTX and PTY.

4.5 Auxiliary Optical Beams

The optical layout must also accommodate the following auxiliary optical signals:

- CO2 heating beams for the Thermal Compensation System (TCS)
- Hartmann Wavefront Sensing Beams for TCS
- Optical Lever Beams (OptLevs)
- Ghost Beam and scattered light control
- Seismic Platform Interferometer (SPI) beams
- Diagnostic beams for the thermal-birefringence, compensated Faraday isolator

The layout requirements for each of these optical beams are discussed in the following subsections.

4.5.1 Thermal Compensation System (TCS) Beams

The Thermal Compensation System (TCS) conceptual design[9] consists of the following primary elements in the optomechanical in-vacuum layout:

1) one CO2 laser heating beam for each CP, expanded to full aperture in the vacuum system

[9] M. Smith, P. Willems, Auxiliary Optics Support (AOS) System Conceptual Design Document, Vol. 1: Thermal Compensation System (TCS), LIGO-T060083-01

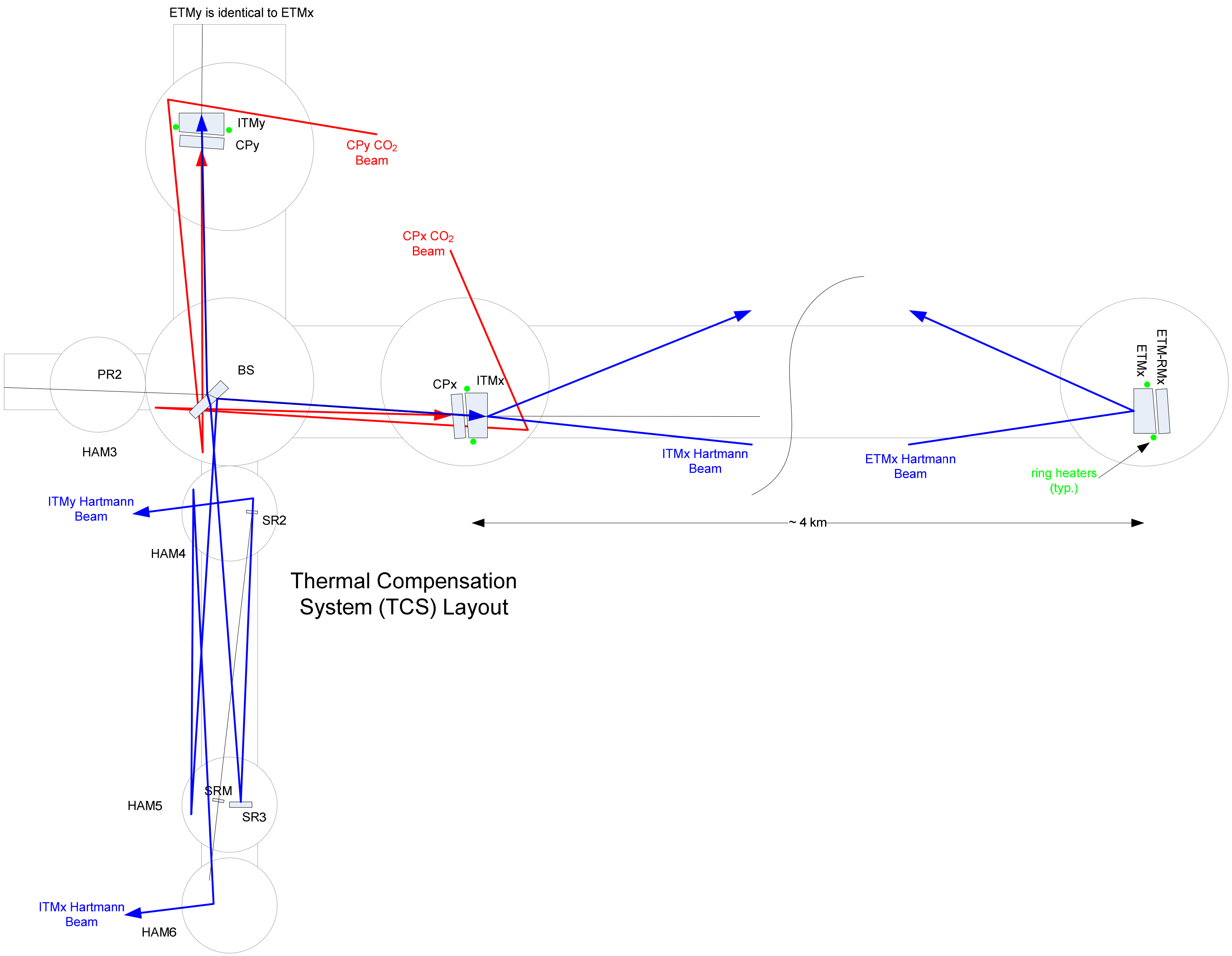
2) one on-axis Hartmann probe through each CP and ITM (injected through an interferometer pick-off port)
3) one Hartmann probe beam reflected off the HR surface of each test mass (although an alternative approach is being explored by the TCS group; see section 7)

Note that the BS Hartmann probe sensor mentioned in the TCS conceptual design (Ref. [9]) is no longer needed since COC has chosen to fabricate the BS with ultra-low absorption fused silica[10].

The CO2 laser system, including stabilization, power control and profile projector are all outside the vacuum system (as in Initial LIGO). The phase cameras which monitor interferometer pick-offs ports are likewise outside of the vacuum system and not part of this integrated layout. (The phase cameras are to be integrated into the ISC optics table layouts.)

[10] H. Armandula, et. al., Core Optics Components Preliminary Design, LIGO-E080033-00

Figure 4: Thermal Compensation System (TCS) Basic Layout



4.5.2 Optical Lever Beams

Optical lever transmitters and receivers are provided by the AOS group. Ideally the motion of all suspended optics would be independently monitored. This goal results in 11 optical levers in the input optics section alone (Ref. [6], section 3.5.1), for each interferometer, as well as a cluttered table and optical lever beams which must bounce off of one or two fixed relay optics mounted to the optics table.

Optical levers for the core optics should not reflect off intermediate relay optics.

4.5.3 Scattered light control

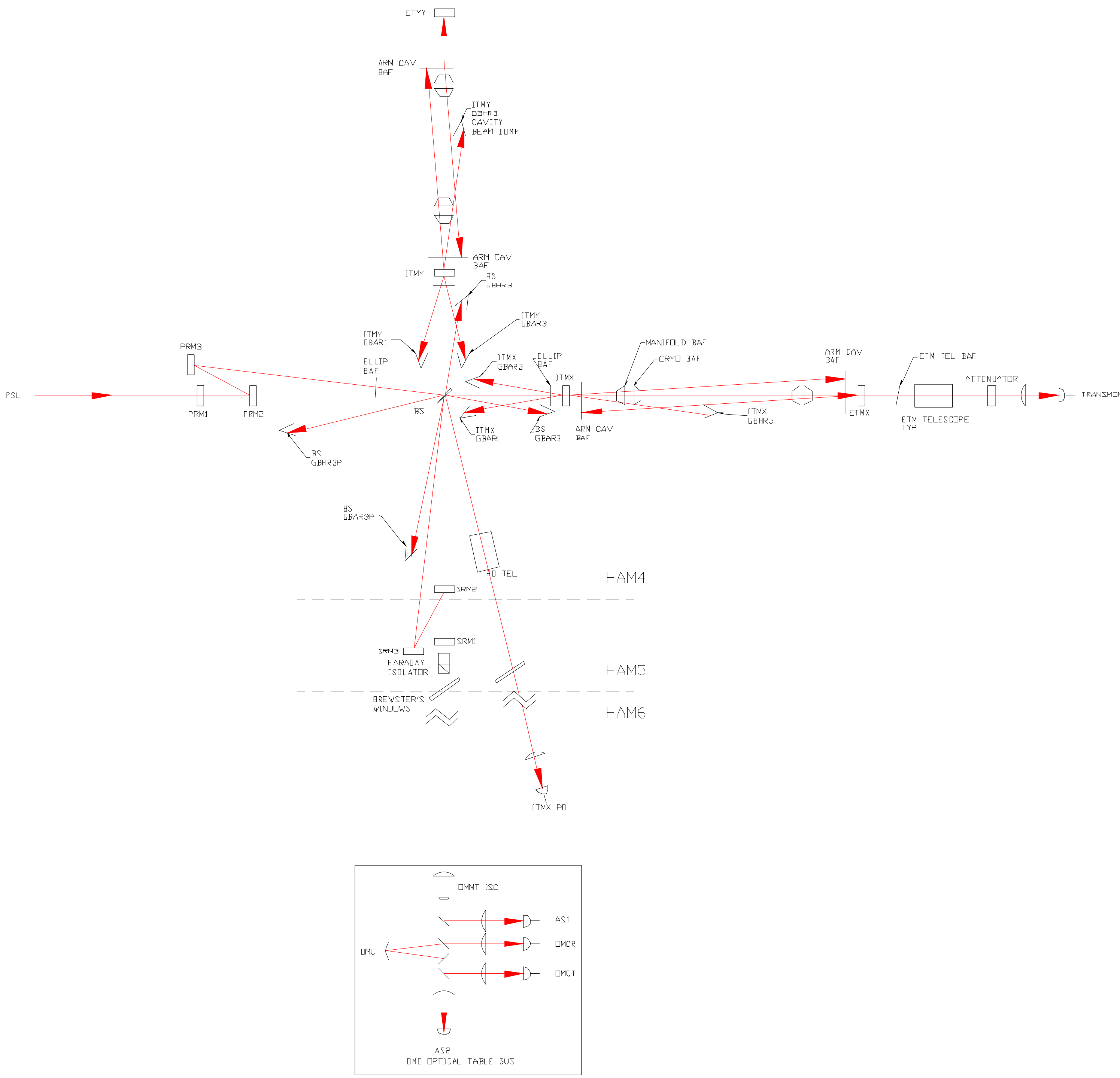
The AOS Stray Light Control (SLC) conceptual design[11] identifies the following major elements:

1) Beam Dumps: absorb the light from ghost beams that originate from the wedged AR surfaces of the core optics mirrors.
2) Arm Cavity Baffles: absorb the small-angle, scattered light arising from the arm cavity mirrors; this is the light scattered from the arm cavity HR mirror surface that propagates 4km to the end of the beam tube, within the far beam tube aperture.
3) Elliptical Baffles: absorb the excess light that spills around the clear aperture of the PRM and the tilted BS.
4) Manifold Baffles: eliminate the reflection of the wide-angle diffuse scattered light from the arm cavity HR mirrors at the viewport spool-piece near the cryopump at the entrance to the arm.
5) Brewster Windows: provide a vacuum barrier between HAM 1 and HAM 2, and between HAM 5 and HAM 6.
6) Cryopump Baffles: obscure the reflecting surfaces of the cryopumps within the arm cavity near the input test mass mirrors.
7) IO Baffle: reduce the passage of scattered light from the input (IO) optics region into the recycling cavity region.
8) Output Faraday Isolator: attenuates light that is back-scattered into the mode of the interferometer from the output optical chain.
9) ETM Telescope Baffle: absorbs the light transmitted by the ETM that is outside the aperture of the ETM beam reducing telescope.

The beam tube/manifold light-scattering analysis Ref. [15] indicated that isotropic scattering from the test masses at high angles (> 15 deg) may exceed the AdL sensitivity spectrum at ~50 Hz and 15 Hz without adequate baffling. The Vacuum Manifold baffles address most of this solid angle range of the BRDF. It remains to be determined if more baffling in the near field is required.

[11] M. Smith, AOS: Stray Light Control (SLC) Conceptual Design, LIGO-T070062-02; N.B.: A significant revision to this report, LIGO-T070062-03, including incorporating stable recycling cavities, will be released soon.

Figure 5: AOS Stray Light Control (SLC) Block Diagram (from T070062-03, see Ref.[11])
The ghost beam naming convention is given in the AOS SLC Design Requirements document[12]



[12] M. Smith, P. Fritschel, AOS: Stray Light Control (SLC) Design Requirements, LIGO-T070061-02, section 2.2

4.5.4 Ghost beam control

All transmissive cavity optics are either wedged (or in the case of the CP, set at an angle to the cavity axis) so that spurious interferometers are avoided. In addition all core optic components have a symmetrical wedge, so that the barrel is not at 90 degrees with regard to the faces, in order to prevent a retro-reflection or glint.

First ghost beams from each optic must be separated sufficiently from the primary beam to allow for optics to capture the ghost beam as a pick-off signal, or for structures to trap or baffle the beam. Each of the primary ghost beams are indicated notionally in the AOS SLC block diagram in Figure Figure 5. Each ghost beam is trapped in a cavity beam dump.

4.5.5 Seismic Platform Interferometer (SPI) beams

Several concepts exist for a arm length stabilizer systems which will simplify lock acquisition of the main interferometer[13]. There are three approaches proposed to date. One relies on the main laser light and so does not require any additional layout considerations. One approach is to implement a Michelson with low finesse arm cavities on small optics mounted to the same platforms as the test masses. The third approach involves injecting a different color of light into each arm through the ETMs and resonating in the arm cavities. Provision is being made for each of these concepts, but they are not shown in the layouts to date.

4.5.6 Diagnostic beams for the input Faraday Isolator

Samples of the transmitted and reflected light both before and after the thermal-birefringence and thermal-lens, compensated Faraday Isolator (FI) are desired by the IO group for diagnostics on this element[14]. These beams, which are available from the polarizers in the FI assembly, are delivered to HAM1/7.

4.6 Optical Materials

All of the glass elements of used for the main interferometer light (1064 nm wavelength) are various grades of fused silica, as defined in the IO and COC design documents. The properties of the surfaces used as baffles or light traps are defined in the AOS Stray Light Control (SLC) design document. The viewports used to inject the TCS CO2 beams are zinc selenide.

5 Constraints and Goals

5.1 Lateral Separation of Interferometer Beams

Since the folded interferometer (H2) shares the same beam tube as the non-folded interferometer (H1), the beams must be laterally separated enough so that the suspension structures of the input and end test masses of the folded interferometer don't clip the beam of the unfolded interferometer.

---

[13] P. Fritschel (ed.), Advanced LIGO Systems Design, LIGO-T010075-01, section 3.15

[14] UF group, IAP group, Upgrading the Input Optics for High Power Operation, LIGO-T060267-00

For our 40 kg fused silica test masses, the diameter is 340 mm. Clearance required for the suspension structure is ~60 mm (one sided). The 1 ppm radius associated with the Fabry-Perot cavity beams is ~158 mm (for a 6cm beam waist on the test masses). Consequently the lateral separation of two interferometer beams should be about 340/2+60+158 = 388 mm or placed at ±200 mm from the beam tube centerline (the same as for Initial LIGO).

Shifting the H1 and H2 optical axes further apart would unnecessarily restrict the width of the TM suspension systems at their upper section to avoid interference with the supporting structures of the seismic isolation system (support tubes and stage-0 structure).

An analysis of the arm cavity light scattering noise[15] indicates that backscatter and diffraction off of the beam tube baffles is not a significant factor with the arm cavity centerlines set within a radius of 224 mm from the beam tube centerline. (The analysis was performed for the arm cavity optical axes at ±200 mm horizontally and -100 mm vertically with respect to the beam tube centerline.)

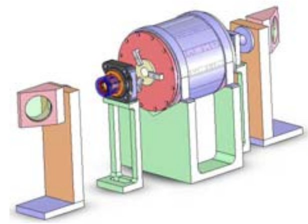
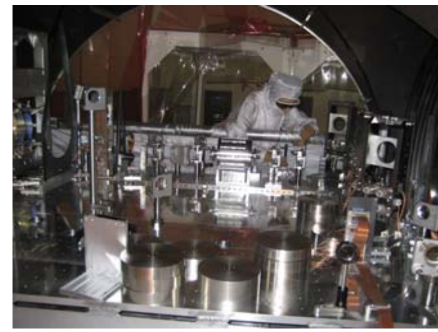
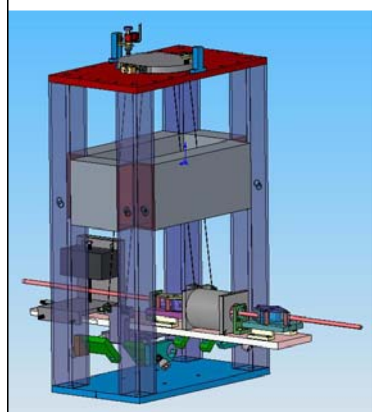
5.2 Optics Table Payload envelopes

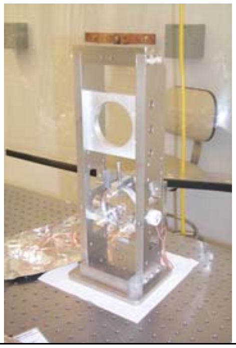
A list of the largest in-vacuum components is given in Table 1, including the group responsible for providing the optic or optical element and the corresponding assembly (or envelope) drawing and a photograph or CAD rendering.. The correspondence between optic and suspension assembly is also provided in the Table. All suspensions are provided by the SUS group, with the exception of SOS suspensions (provided by IO) and AOS provided passive, single pendulum suspensions.

A number of smaller or less significant components are not listed in Table 1, including fixed or adjustable (non-suspended) optic mounts, counter-balance mass (used to make up the full payload mass and to balance the SEI optics tables) and errant beam baffles.

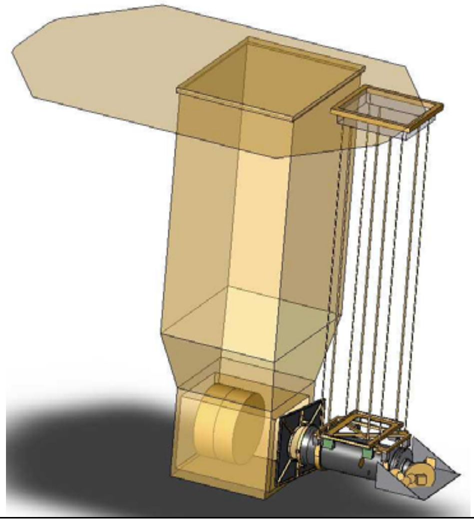
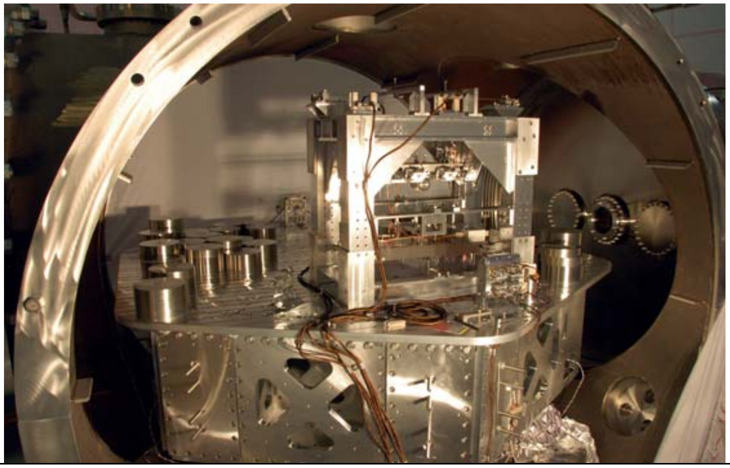
[15] K. Thorne, Scattering Noise for Advanced LIGO – Version 2, 26 May 2006, (no LIGO document number)
This document is based on the data in the following document:
A. Lazzarini, Inputs to Beam Tube Scattering and Optical Surface Roughness Requirement Analysis for Advanced LIGO, LIGO-T060013-02
and is an update to the analysis for Initial LIGO documented in the following memo:
E. Flanagan, K. Thorne, Scattered-Light Noise for LIGO, LIGO-T950132.

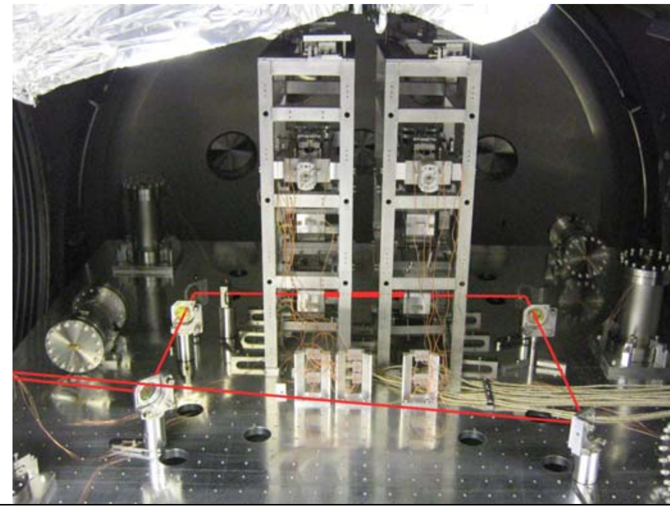
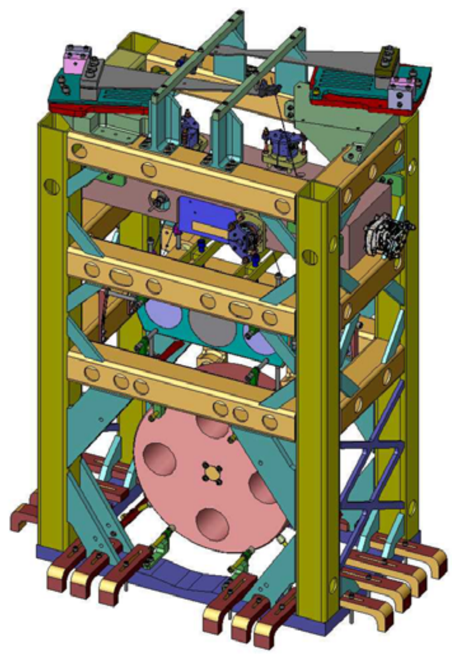
Table 1: Payload Elements for the Optics Tables

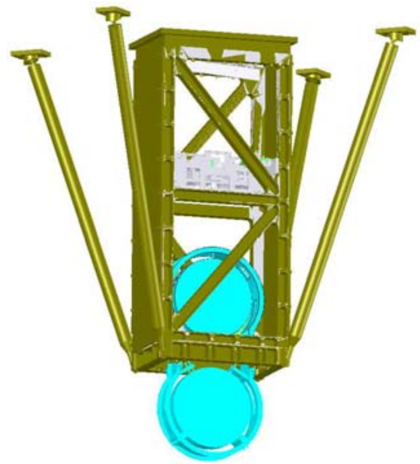
Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering
IO	Input FI (IFI)	NA	TBD	  ELI @ LLO
AOS	Output FI (OFI)	TBD [single]	TBD	 The output Faraday Isolator needs additional isolation than provided by the HAM SEI. A single pendulum with passive damping plus a means to statically adjust pitch is anticipated. The design depicted here is in a modified LOS suspension structure.
ISC	Tip-Tilt Mirrors: designations TBD	Tip-Tilt Stage [single]	D070170-00	 Prototype Tip-Tilt stages, using the Birmingham-style OSEMs (B-OSEMs) are being deployed for Enhanced LIGO. For Advanced LIGO we anticipate using pairs of Tip-Tilt stages where fast and high dynamic range angular control is needed; Perhaps just the AS and REFL ports.

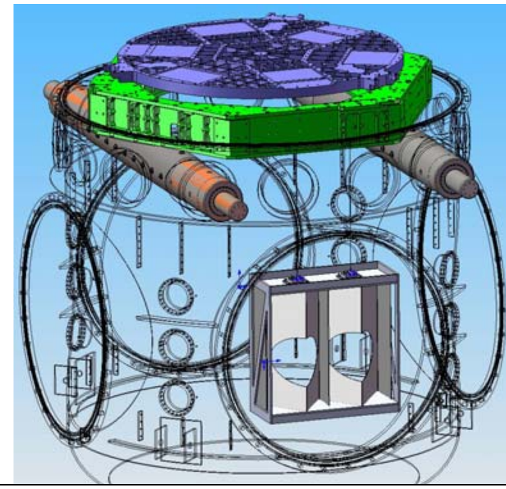
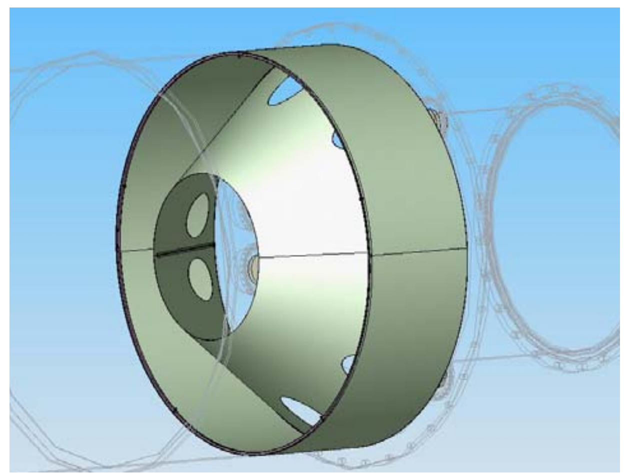
Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering
IO	Steering Mirrors: SM1, SM2, SM3	Small Optic Suspension (SOS) [single]	D960001-D	 An Initial LIGO SOS assembly.
AOS	ITMx pick-off telescope element 2: POX2			
AOS	ITMx pick-off telescope element 1: POX1	Large Optic Suspension (LOS)[16] [single]	D970578-A	 An initial LIGO LOS (the MMT3) shown in a HAM chamber.

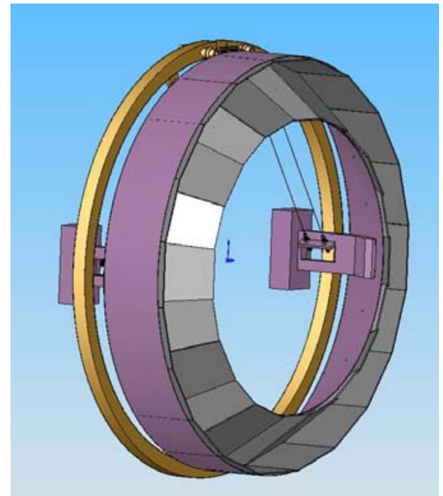
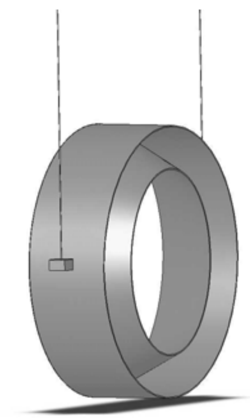
[16] There are different types of LOS suspensions depending upon the optic wedge angle. The drawing called out in this table is for variant LOS1a used for the Initial LIGO MMT3 optic.

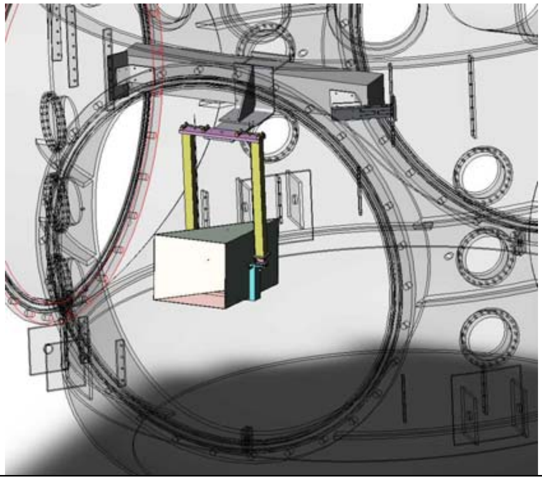
Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering	
AOS & ISC	ETM transmission telescope	ETM transmission telescope [single]	TBD		The ETM telescope is shown behind the envelope model of the ETM quad suspension. Both are mounted to the BSC optics table. The ETM telescope baffle is also shown (it is integral with the telescope assembly). The optics and detector at the output of the telescope are provided by ISC.
ISC	Output Mode Cleaner (OMC) bench	OMC Suspension [double]	D080125 (LHO) D060306 (LLO) D060104-07 (envelope)		The prototype OMC for Enhanced LIGO is shown in LHAM6 atop the prototype HAM Internal Seismic Isolation (ISI) system.

Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering	
IO	Input Mode Cleaner (IMC) optics: IMC1, IMC2, IMC3	HAM Small Triple Suspension (HSTS) [triple]	D020700-A		Two small triple suspension assembles are shown in testing at the LASTI facility in a HAM chamber (with the optics table set to the AdL height).
IO	Power & Signal Recycling Cavity small optics: PRM, PR2, SRM, SR2				
COC	Power & Signal Recycling Cavity large optics: PR3, SR3	HAM Large Triple Suspension (HLTS) [triple]	D080015-00 (D070447-00?)		The preliminary design of the HAM large triple suspension is depicted. Fabrication of a prototype/first article has begun.

Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering
COC	Beam Splitter (BS)	Beam Splitter (BS) [triple]	TBD TD-1113-090	 The outriggers may not be needed to meet stiffening requirements (under evaluation). If outriggers are needed, they are likely to not extend as far and we will have some flexibility in positioning where they land on the optics table. A prototype system is being built by SUS.
COC	Fold Mirror (FM)			
COC	Input Test Mass (ITM) & Compensation Plate (CP)	Test Mass Suspension [quadruple]	TBD TD-1084-090, rev. 03 (D050266-00 envelope)	 The 2nd generation prototype of the E/ITM suspension (the “noise” prototype) installed on a BSC ISI optics table at LASTI. (The lower suspended metal masses are ersatz optics.)
COC	End Test Mass (ETM) & Reaction Mass			

Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering
AOS	Arm Cavity Baffle (ACB)	NA [single, passive]	TBD	 The Arm Cavity Baffle Assembly is shown in the context of the ITM and ETM BSC chambers. The ACB is suspended from the BSC-ISI stage-0 structure (shown in green).
AOS	Vacuum Manifold Baffle	NA [single, passive]	TBD	 The vacuum manifold baffle placed in the existing vacuum manifold tubes just before the ring of viewports which face the TMs. The current concept also forms a conical light trap cavity in the opposing direction as well. The assembly is suspended from a ring which is expanded against the manifold inner diameter.

Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering
AOS	Cryopump Baffle	NA [single, passive]	TBD	 The cryopump baffle is a conical light trap which is suspended from a ring which is expanded against the inner diameter of the tube. (The current concept employs black porcelain glazed sheet and not faceted black glass panels as depicted here.)
AOS	Elliptical Baffle	NA [single, passive]	TBD	 The elliptical aperture baffles are hung from the BSC-ISI support ring (stage-0) on the AR side of the ITMs. To prevent the baffle from swinging into anything, motion limiting stops will be anchored to adjacent chamber attachment points.

Grp	Optic(s) or Optical Element	Suspension [type]	Assembly or Envelope dwg	Picture or CAD rendering
AOS	Cavity Beam Dumps (traps)	NA	TBD	 The rectangular aperture cavity light traps are supported by beams which span between chamber attachment brackets (just as in Initial LIGO).

5.3 Optics Table Mass Limits

The mass of the ensemble of payload elements which are placed onto the in-vacuum optics tables, plus the mass required to balance the tables, must not exceed the design limits. The design requirements were based on early conservative mass estimates for various optics table layouts. The payload mass estimates[17] for the optical layout discussed in this document, and the companion detailed layout document Ref. [2], indicate an adequate margin between the requirements of this layout and the design capacity of the ISI systems.

5.4 Height Considerations in the Chambers

The beam heights and basic envelope dimensions for the key assemblies placed on the chamber optics tables are listed in Table 2.

Table 2: Beam Heights[18] and Basic Envelope Dimensions for Key In-Chamber Optical Assemblies

All dimensions are in mm. Heights are relative to the optics table surface. Depth is in the direction of the optical element thickness.

Assembly	Beam Height	Optic Dia.	Optic Thickness	Height	Width	Depth
SOS	140	75	25	417	156	127
HSTS	140	150	75	866	425	245
HLTS	158	265	100	818	480	300
BS & FM	-1742*	370	60	2154*	560 @ optic 710 @ table	350
E/ITM	-1742	340	200	1960	460 @ optic 710 @ table	585

* These dimensions will be reflected in a pending change to the envelope drawing (TD-1113-090) for the BS and FM suspensions to reflect the decision to use horizontal wedge angles.

In the following subsections some considerations of beam heights in the two chamber types are discussed.

5.4.1 BSC Chamber

The arm cavity height was set in the baseline layout (system conceptual design[19]) to be at -80 mm in the global coordinate system. This beam height was motivated by the elevation change resulting from vertical wedge angles chosen to separate pick-off beams and ghost beams in the marginally stable recycling cavities. Although in principle the arm cavity beam height can be adjusted, the

[17] D. Coyne, Seismic Isolation System (SEI) Payload Mass Properties, LIGO-E040136-01 (pending)

[18] N.B.: The layout reported in the companion document, T080078-01, has incorrect beam heights for the SOS and HSTS suspensions (100 and 140 instead of 140 and 158 mm for the SOS and HSTS, respectively). These height changes can be readily accommodated by pitching the beam down from PR3/SR3 to PR2/SR2.

[19] D. Coyne, Optical Layout for Advanced LIGO, LIGO-T010076-01, section 8.2

BSC-ISI and SUS-E/ITM designs are based on this height; to change now would require (re)design effort. However a small or modest lowering of the height could be accomplished with the addition of a spacer between the E/ITM suspensions and the optics tables, with minimal impact on the dynamics and control of the coupled BSC-ISI and E/ITM suspension system.

5.4.2 HAM Chamber

The HAM optics table height, in the LIGO global coordinate system was uniformly set at -200 mm (in the LIGO global coordinate system) for initial LIGO. The same height will be used for Enhanced LIGO for all HAM optics tables, including the additional HAM-ISI prototype table added in HAM6 (for interferometers H1 and L1 only). For Advanced LIGO the HAM optics table height[20] shall be capable of being set to either -200 mm or -325 mm (Figure 6). The motivation for two HAM optics table heights is the need for headroom height for some of the triple suspension assemblies for AdL and the desire to minimize the number of periscopes (and/or height adapters for payload elements) required for optical beams to exit the chambers through the (much higher) viewports. (The HAM chamber viewports centers are at -91 and +238 mm.) The limited height above the optics table in the HAM chambers places a significant constraint on the height of the suspension assemblies[21].

In many AdL IO layouts scenarios explored to date, the MC triple suspensions were placed on riser blocks to facilitate a beam height that is compatible with the viewport height without needing multiple periscope assemblies. In other layout scenarios, the placement of the MC triples may preclude raising them due to the sloped HAM ceiling. Moreover, for future enhancements or revisions we would like to have some margin in the ceiling height and so do not want to set the height irrevocably high. At this time, the HAM-ISI design is complete and with two prototypes built for enhanced LIGO, the minimum HAM height of -325 mm should be taken as a firm lower bound.

A summary of the HAM optics table heights is given in Table 3.

5.5 Repair access for the TMs

In the event of a failure of the fused silica fiber or ribbon which suspends the test mass, the lower section of the suspension must be removed from the chamber through the BSC chamber door[22]. For the folded interferometer (H2), the arm cavity axis must be set to the side opposite of the chamber door, so that the ITM suspension does not block the FM suspension from being removed (and vice versa).

[20] RODA: HAM Optics Table Height, LIGO-M070119-00

[21] D. Coyne, "Available Height above the HAM Optics Table", LIGO-T000087-01.

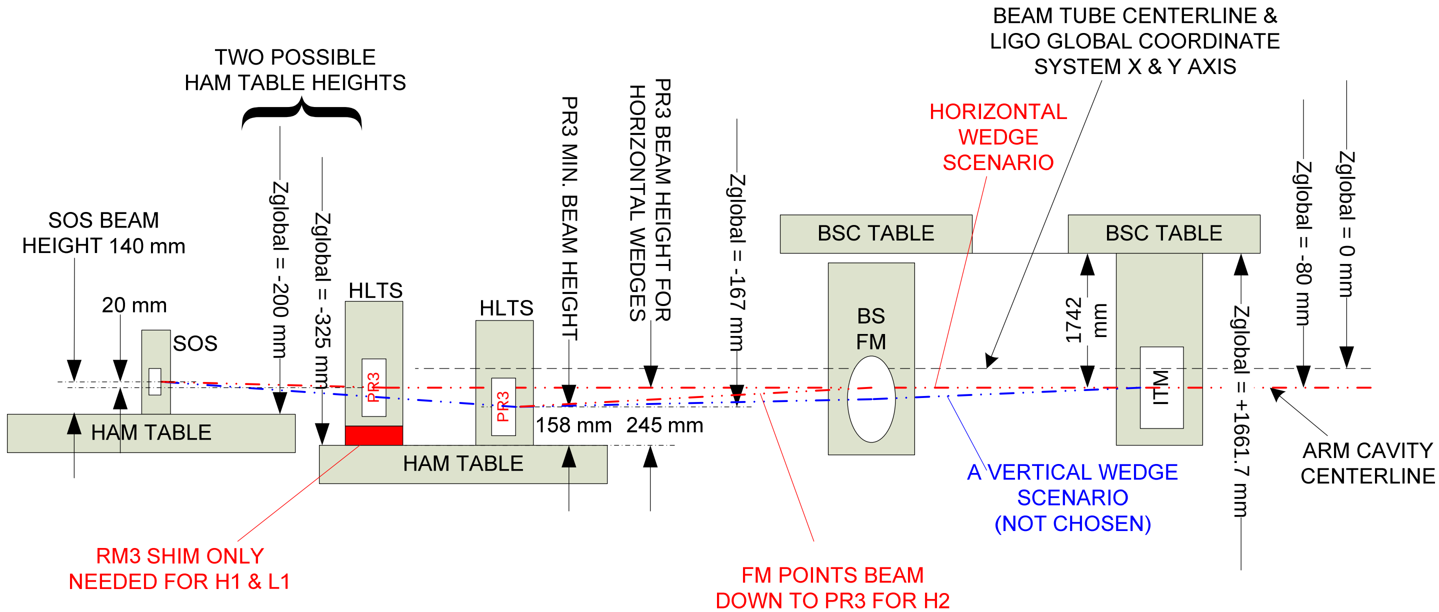
[22] J. Romie, Advanced LIGO Quadruple Pendulum Suspension Failure Modes and Subsequent Repair Approaches, LIGO-E040329-03

Table 3: HAM Table Heights

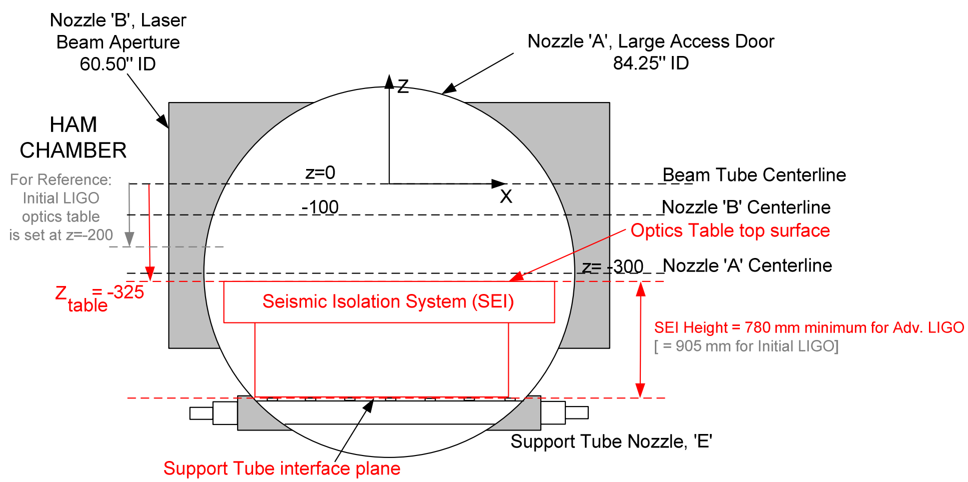
Chamber	Height (Z_{global}, mm)	Comments
HAM1/7	-200	Reflected port ISC readout & IO readout table. Initial LIGO optics table on a TBD seismic isolation system.
HAM2/8	-325	IO table with one end of the MC and one end of the input MMT within the PRC; the lowest table height is required for PR3
HAM3/9	-200 or -325	IO & PRC table with one end of the IMC cavity and one end of the input MMT; height depends on specific positions of the two HAM small triple suspensions relative to the chamber ceiling
HAM4/10	-200 or -325	OO & SRC table with one end of the output MMT; height depends on specific positions of the two HAM small triple suspensions relative to the chamber ceiling
HAM5/11	-325	OO & SRC table with one end of the MMT within the SRC; the lowest table height is required for PR3
HAM6/12	-200	Dark port ISC readout table.

Figure 6: Height Considerations in the Chambers

(a) Nominal beam height in the HAM chambers depends on interferometer, vertical wedge angle component (if any) and specific chamber



(a) Tall suspensions (HSTS, HLTS) cannot be placed in the four quadrants of the tables where the intersection of the two shells which form the HAM chamber is low. It is best to keep the tall suspensions toward the centers of the A and B nozzles.

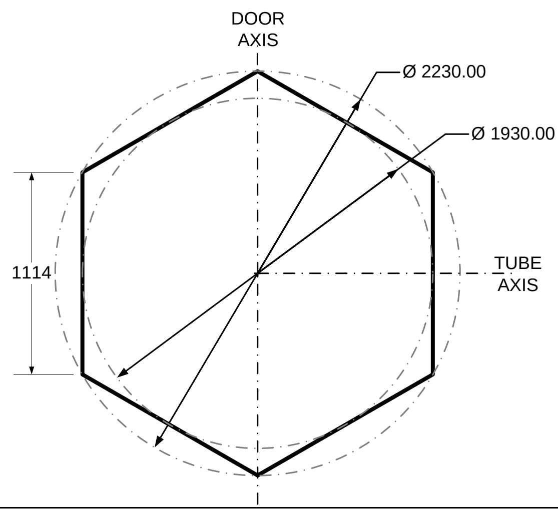
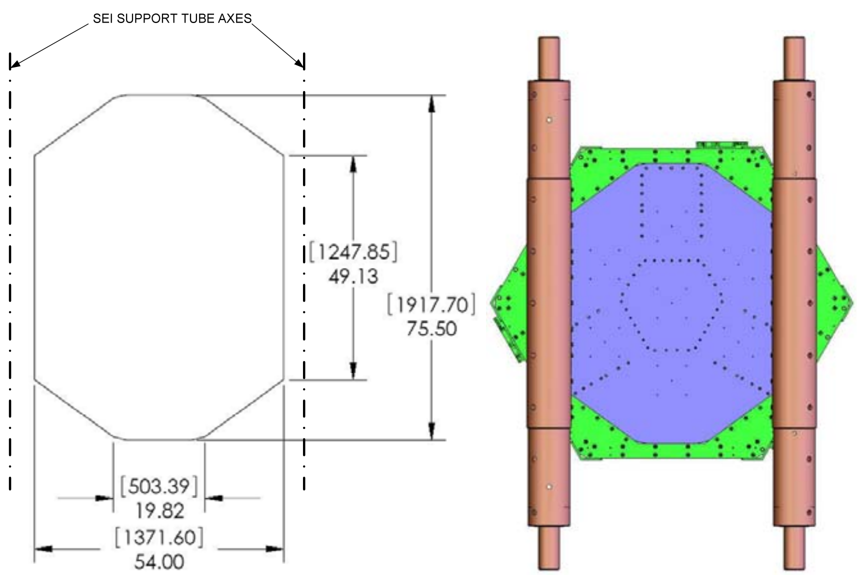


5.6 Optics Table Envelopes

The basic dimensions of the space available for mounting payload on the optics tables in the HAM and BSC chambers is given in Table 4. Both the HAM and the BSC optics tables are centered in their respective chambers.

In general no payload elements should overhang the HAM table. It is not possible to overhang the BSC table since the planform limits are determined by the support tubes and the stage-0 ring structure (as indicated in the image in Table 4). The support ring and support tubes (which are isolated by the BSC-SEI HEPI system) can be used to mount modest weight items.

Table 4: Basic Dimensions of Optics Support Platforms

Optics Platform	**Dimensions** (dimensions in mm, or inch [mm])
HAM Optics Table	
BSC Optics Table & Stage-0 Support Ring	

5.7 Wedge Angle Orientation

The orientation of the COC surfaces with respect to the local gravity vector causes a coupling of seismic and thermal vertical motion to length motion[23]. The noise due to this coupling for the Power Recycling Cavity (PRC) and Signal Recycling Cavity (SRC) surfaces should be much smaller that the contribution due to the Fabry-Perot (FP) cavity surfaces. The allowable contribution to the noise floor for each RC surface was set at 1/10 of the contribution due to each FP surface (Ref. [19], Appendix 1). In general, since the isolation of the PRM and SRM is less than for the ITMs, an optical layout that minimizes the beam's deviation from horizontal at the PRM and SRM is much preferred.

The optomechanical layout considerations previously focused on vertically wedged core optics. The reasons for this are as follows:

1) There is an inherent vertical shift in the beam line between the beam tubes and the main beam line apertures of the HAM chambers. This vertical height difference is accentuated by lowering the optical tables in the HAM chambers to accommodate taller suspensions in advanced LIGO. Given the height considerations mentioned section 5.4, bringing the beam down to the lower AdL HAM tables height means ~0.5 deg ITM vertical wedge component or an even larger BS vertical wedge component.

2) There was a perceived desire to provide three recycling cavity pickoff beams (as was the case for Initial LIGO). There did not appear to be sufficient real estate on the optics tables to accommodate the multiple pickoff mirrors and telescope structures with horizontally splayed beams.

3) Scattering considerations in the beam tubes necessitates keeping the centers of the two interferometer beams well away from the baffle edges. Physical constraints in the size of the suspensions set a minimum separation laterally between the interferometer beams. Together these two constraints set the minimum vertical height at approximately -100 mm; higher than the beam height in the HAM chamber.

Reasons for re-visiting the vertical wedge design baselined at the conceptual design review and considering horizontal wedges or a hybrid approach with some vertical and some horizontal wedges:

1) Cavity length considerations may permit placement of the suspensions near the centers of the two cylindrical shells which form the HAM chambers, in which case there is considerably more headroom height and the suspensions can be raised (and possibly the optics table as well).

2) Two recycling cavity pickoff beams have been deemed adequate. Moreover one of these beams is available as the transmitted PR2 beam as a consequence of the decision to switch to a stable power recycling cavity.

3) The scattering function is a very weak function of the separation distance for the small changes we are considering (Ref. [15]).

[23] D. Coyne, Optical Coupling of Vertical Displacement to Cavity Length, LIGO-T040007-00

4) A horizontal wedge for the BS allowed switching from fused silica to carbon steel suspension wires[24] with a resulting reduction in complexity. An analysis[25] of the effects of the horizontal wedge in coupling to length through roll and side-to-side motion, for the BS, indicated that the coupling was negligible.

5.8 Wedge Angle Magnitude

The maximum wedge angles, from manufacturing considerations for high precision optics, are 1° 0′ for the BS and FM and 3° 0′ for the ITM, ETM, PR3 and SR3 optics. The wedge angle tolerance[26] is ± 1′. As in Initial LIGO, all wedges are to be symmetric, i.e. each surface is set at one-half the wedge angle relative to the cylindrical axis of the optic. This prevents an internal retro-reflection from a 90° interface between a face and the cylindrical surface. The symmetry of this arrangement also minimizes cross-coupling in the suspension modes.

Commonality of wedge angles for like-sized optics is desired. The wedge angle for the Beamsplitter (BS) for the folded and the unfolded interferometers, as well as the Folding Mirrors (FM), should be the same. Likewise the wedge angles of the PR3 and SR3 optics should be the same. The ETM and ITMs for both folded and non-folded interferometers should be the same.

6 Design

Details of the optomechanical layout are provided in the companion document, T080078 (Ref. [2]), as well as the AOS Stray Light Control (SLC) design document, T070062-03 (Ref.[11]) and the AOS Thermal Compensation (TCS) design document, T060083-01 (Ref. [9]). The stable recycling cavity layout shown in the IO Preliminary design document, T060269-02, (Ref. [6]) is reasonably close to the version in T080078, but details on positions of the optics are different. Below a few of the highlights are summarized.

6.1 Approach

The optomechanical layouts are maintained in Zemax™ and SolidWorks™. The SolidWorks™ CAD models are maintained in a PDMWorks™ vault for shared secure access across the project, with check-in/out and change tracking.

6.2 PSL Beam Injection Location

We cannot route the PSL beam in front of the main doors to the HAM2 chamber for injection through the door viewports since this interferes with installation needs for access. We considered bringing the beam under the chamber and through the HAM ISI table but this seemed a needlessly complex solution which made access to the steering mirrors and light path covers difficult once installed. Routing the beam over the chambers and then in through a port in the top of the HAM chamber suffers from the need to make tall, stiff structures to support the steering mirrors.

---

[24] RODA: Beamsplitter Optic Size, Geometry, Wedge Orientation and Suspension Wire Material, LIGO-M070120-02

[25] D. Coyne, N. Robertson, Indirect Length Coupling for the Beamsplitter with Horizontal Wedge, LIGO-T070153-01

[26] The wedge angle tolerance in Initial LIGO was ± 5', but far better accuracy was achieved. A smaller tolerance is desirable. The specification here is subject to further review.

We have elected to bring the beam into HAM2 by going through HAM1. Since there will be a vacuum septum plate between HAMs 1 and 2, this PSL path must allow for different vacuum states for the two chambers. This PSL beam path will of course need to be covered by a tube for personnel and machine/detector safety.

6.3 Horizontal Wedge Orientation

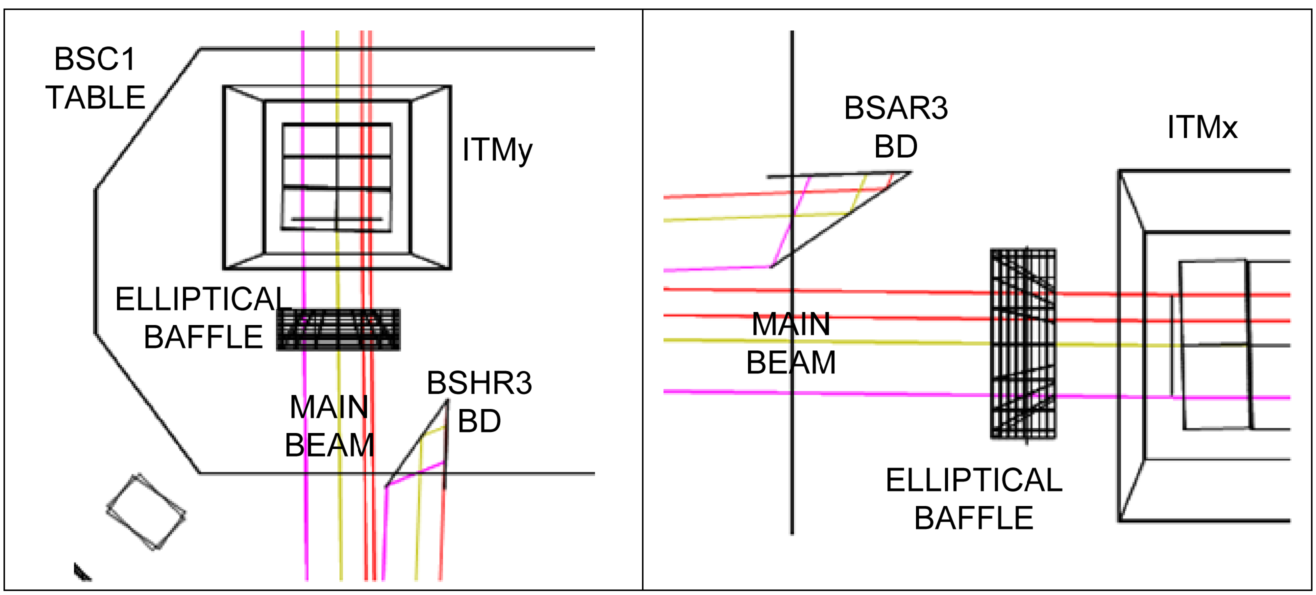
We have managed to implement an optical layout that meets all requirements and has only horizontal wedges. This was accomplished in the H1/L1 interferometers by shifting the positions of the ITMs and BS, and selecting appropriate wedge angle signs, in order to place the PR3 (SR3) optic near the center of the HAM chamber. The stable PRC (SRC) geometry also allows freedom in shifting the relative positions of PRM, PR2 and PR3 (SRM, SR2 and SR3), while maintaining cavity length. A spacer will be required under the H1/L1 PR3 suspension.

For the H2 interferometer it was necessary to place the PR3 (SR3) suspension as low as possible on the HAM optics table. The height change is accomplished with pitch angles for both FMs.

6.4 COC Wedge angle determination

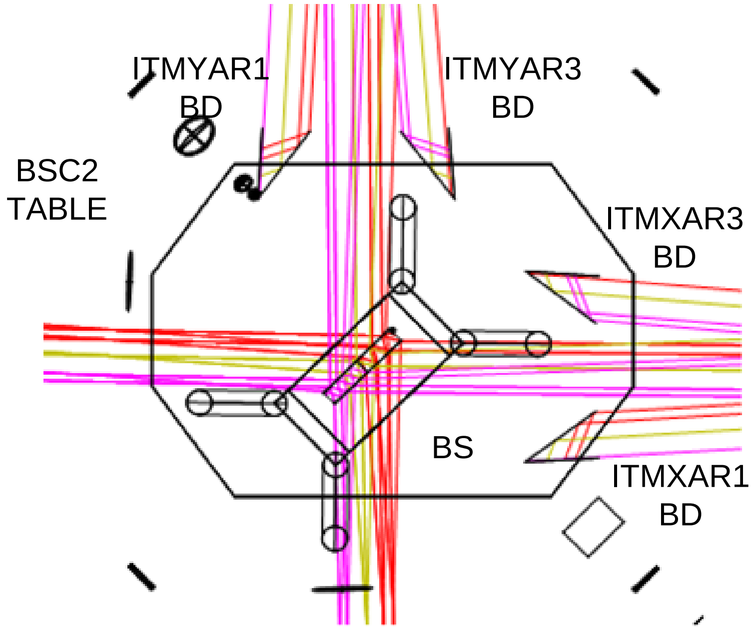
The BS wedge angle determines the clearance between the edge of the recycling cavity main beam and the edge of the cavity beam dumps which catch the first ghost beams reflected off of the BS AR and HR surfaces (Figure 7).

Figure 7: Separation and trapping of the BS first order ghost beams



The combined ITM and CP wedge angle determines the clearance between the edge of the recycling cavity main beam and the edge of the cavity beam dumps positioned to catch the 1st and 2nd ITM ghost beams (Figure 8).

Figure 8: Separation and trapping of the ITM first and second order ghost beams



Specific wedge angles are cited in the companion document, T080078.

7 Open Design Issues

The following are open design issues, or known problems, to be resolved in the final design phase:

1) Astigmatism resulting from BS wedge[27]: May require reduction of the BS wedge angle, requiring the layout to be "squeezed" a bit (reduction of a factor of ~2 is possible). Alternatively we might provide a compensating polish or astigmatic corrector in the recycling cavities.

2) Definitively set the minimum FM and ITM separation: There is a RODA being prepared. We know that we can separate the FM and ITM suspension structures. However, we need to establish the minimum required separation distance so that the suspension envelopes can be finalized.

3) Consider laterally shifted BSC-ISI design?: Given that the BSC optical layouts are less complex, less massive and less cluttered than originally estimated (no pick-off mirrors, no E/ITM outriggers), one could shift the BSC-ISI system laterally to reduce the required balance mass. This change could add some small additional Schnupp asymmetry range, but reduces the total available optics table area. The reduction in stage 2 mass may also increase the influence of the E/ITM structural resonances on the ISI control. This change would require a redesign of the stage-0 structure and the blade flexures for both stages.

4) Resolve whether outriggers are required for the BS and FM suspensions

[27] H. Armandula, et. al., Response to Comments and Questions on the COC Design Requirements Document (DRD), LIGO-L080029-00, Item 11.c

5) Define acceptable wedge angle tolerances and/or evaluate the layout for realizable tolerances.
6) Seismic Platform Interferometer: Resolve the approach to be used for an arm length stabilizer system for lock acquisition. Implement in the integrated optomechanical layout.
7) Refine and complete the detailed 3D layout in SolidWorks™ to insure that there are no interferences. To date most of the layout has been done in Zemax™ using simplified 3D representations of the payloads and infrastructure.
8) Reduce the Optical Lever quantity or scheme (currently trying to monitor every suspended optic) to a more practical approach.
9) Revised ETM Hartmann Sensing approach: The AOS/TCS group has an alternative wavefront sensing approach under evaluation for the ETMs. Instead of a Hartmann probe beam reflected off of the HR surface of each ETM, an optical lever would be used plus a temporary Hartmann sensor used to probe the ETM HR surface through the AR side.
10) Determine if the vacuum manifold baffles are sufficient to address high angle backscatter from the test mass optics.