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Mode Matching Telescope for Advanced LIGO Output Mode Cleaners

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1 Introduction

Advanced LIGO (aLIGO) output mode cleaner (OMC) mode matching telescope ensures that the optical mode of the laser beam coming from the signal recycling mirror is well matched to the Eigenmode of the OMC. The telescope mirrors double as the steering mirrors. In this document, parameters for the aLIGO OMC mode matching telescope are shown.

1.1 Conventions

For the coordinate system we follow the aLIGO convention as in Reference [**??**], but we ignore the vertical dimension as the beam paths are all nearly horizontal for the purpose of this document.

We also use acronyms such as:

ROC: Radius Of Curvature

SRM: Signal Recycling Mirror

TT: TipTilt mirror

OMC: Output Mode Cleaner

POS: POSition of the mirror along the optical axis

2 Design Principle

OMC geometry, signal recycling cavity geometry and location, and HAM chamber locations are explicitly given (see the next subsection). Under this constraint, the mode matching telescope should satisfy three conditions:

- It should fit in the vacuum enclosures (HAM5 and HAM6 for H1/L1, HAM11 and HAM12 for H2).
- The Gouy phase difference between the two telescope mirrors used for controling the alignment into the OMC should be reasonably close to 90 degrees so that two control signals don't become degenerate. This is not of critical importantce, but in this

document we reject any solution that is smaller than 70 degrees or larger than 110 degrees.

- Amplitude of the higher order modes caused by motions of the telescope optics should be as small as possible.

In the design process, two-mirror solutions were first searched by changing the ROC of each of the mirrors as well as the positions of the mirrors and the OMC within the above mentioned conditions while monitoring the higher order mode misalignment/mismatching coupling.

After the good parameters were obtained, a third flat mirror was inserted at a convenient place without changing the mode matching to make sure that the initial alignment procedure becomes easier in the installation phase.

Though the higher order mode coupling was calculated for angular motion, displacement vertical to the mirror surface ("POS") and the lateral (i.e. parallel to the mirror face) displacement, it was found that the second one is about three orders of magnitude smaller than the last one (see Section 3), and therefore was not used as a figure of merit of the design. Instead, since the vertical (i.e. z-) direction is least isolated from the external vibrations, and since this caused a problem in eLIGO, the parameters that give the least amount of lateral coupling was chosen as the best set, but the angular coupling was also checked because in eLIGO that coupling cannot be ignored.

The proposed parameters were checked to make sure that the aLIGO angle and lateral coupling are at least about the same as eLIGO L1 (which means that aLIGO is much better than eLIGO H1).

2.1 Design Boundary Conditions

For the purpose of this document, several parameters are explicitly given as the boundary conditions: ROC and the beam radius on SRM defines the modal shape upstream of the mode matching telescope, OMC waist defines the target modal shape downstream, and the placement of the SRM and vacuum chambers put a practical limitation on the placement of

Beam parameters	SRM ROC	SRM beam radius	OMC waist radius
	-5.69 m	2.1e-3 m	5.09e-4 m

Table 1: aLIGO L1/H1 beam parameters.

Component	SRM (on HAM5)	HAM5 (center)	HAM6 (center)
Position (mm)	(306.4, -19858.8)	(0, -20122)	(0, -22692)

Table 2: aLIGO L1/H1 component locations.

the mode matching optics and the OMC.

Table 1 lists the beam parameters [1, 3].

2.2 Note About the Coupling Between Optics Motion and Misalignment/Mismatching

Suppose that, for a given set of parameters, the mode coming out of the interferometer is perfectly matched to that of the OMC.

When only one of the mode matching optics moves in angle or in lateral/vertical displacement or in POS displacement, a small mismatching is induced.

For example, suppose that the mode structure immediately downstream of the optic which moved by δz in the vertical direction is written by

$$U_0 + (A + iB)\, U_1 \delta z$$

where U_0 and U_1 are the 0-th and first order mode of the OMC eigenmode propagated to the optic position, A and B represents the sensitivity of the mode matching to the motion δz. In this case we can define the normalized amplitude of the mismatching coupling as

$$c = \sqrt{\frac{A^2}{w_0^2} + \frac{B^2}{\theta_0^2}}$$

where w_0 and θ_0 are the waist radius and the divergence angle of U_0.

We can make a similar argument to the displacement of the optics in the direction of the

Optics	SRM		TT1		TT2		TT3		OMC
ROC or distance (m)	-5.69	3.646	4.6	1.395	1.7	0.708	flat	0.268	waist=5.09e-4

Table 3: Proposed telescope parameters.

	Angle×1e3 (1/rad)	Lateral×1e3 (1/m)	POS (1/m)
TT1	3.6	0.78	0.91
TT2	4.9	2.9	0.22
TT3	3.4	0.0	1.3
All	7.0	3.0	1.6

Table 4: Coupling of TT motion to normalized mismatching/misalignment amplitude. "All" represents the square root of the square sum of all optics.

light propagation as well as the tilt of the optics. These are explained in References [4] and [5].

3 Proposed Design

Table 3 shows the proposed design parameters of the mode matching telescope, and the coupling numbers are in Table 4. For comparison purpose, Table 5 lists the coupling numbers of eLIGO. The important couplings, i.e. bounce and angle,[1] are about a factor of 6 to 7 better than the eLIGO H1. Compared with eLIGO L1, angle coupling is about a factor of 1.6 better and the lateral coupling is about a factor of 1.8 worse.

Figure 1 shows the beam size and Gouy phase along the beam propagation axis. Absolute value of Gouy phase difference (modulo 180 degrees) between TT1 and TT2 as well as TT1

[1] It is apparent from these tables that the POS coupling (the coupling for the optics motion vertical to the mirror fase) is about three orders of magnitude smaller than the bounce coupling. Angle coupling is still important for magnetic coupling etc., but readers can safely ignore the bounce coupling.

	Angle×1e3 (1/rad)	Lateral×1e3 (1/m)	POS (1/m)
TT0 [L1, H1]	[8.1, 40]	[0, 15]	[0.24, 39]
TT1 [L1, H1]	[7.4, 6.7]	[1.5, 13]	[0.61, 31]
TT2 [L1, H1]	[3.1, 3.3]	[0.8, 1.6]	[1.2, 0.89]
All [L1, H1]	[11, 41]	[1.7, 20]	[1.4, 50]

Table 5: eLIGO TT motion coupling to normalized mismatching/misalignment amplitude. "All" represents the square root of the square sum of all optics.

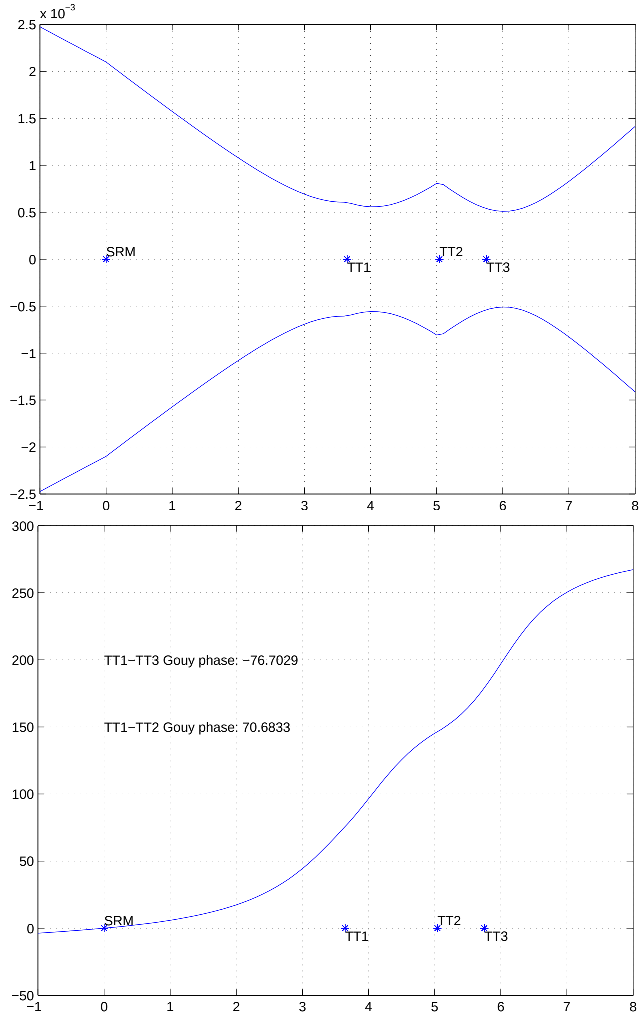

Figure 1: Beamsize and Gouy shift along the beam propagation.

and TT3 are both about 70 degrees, which is not excellent but good enough. Either of these two combinations can be used for the angular control.

Figure 2 shows the placement of optics inside HAM5/HAM6. Small rectangles at the position of TTs represent the footprint of the bottom plate of the proposed aLIGO TT. Larger square at around the center of HAM6 shows the footprint of the OMC breadboard. Since TT3 is flat, TT3 and OMC could be moved at the same time in such a way that the distance from TT2 to OMC doesn't change. This gives some room of adjustment.

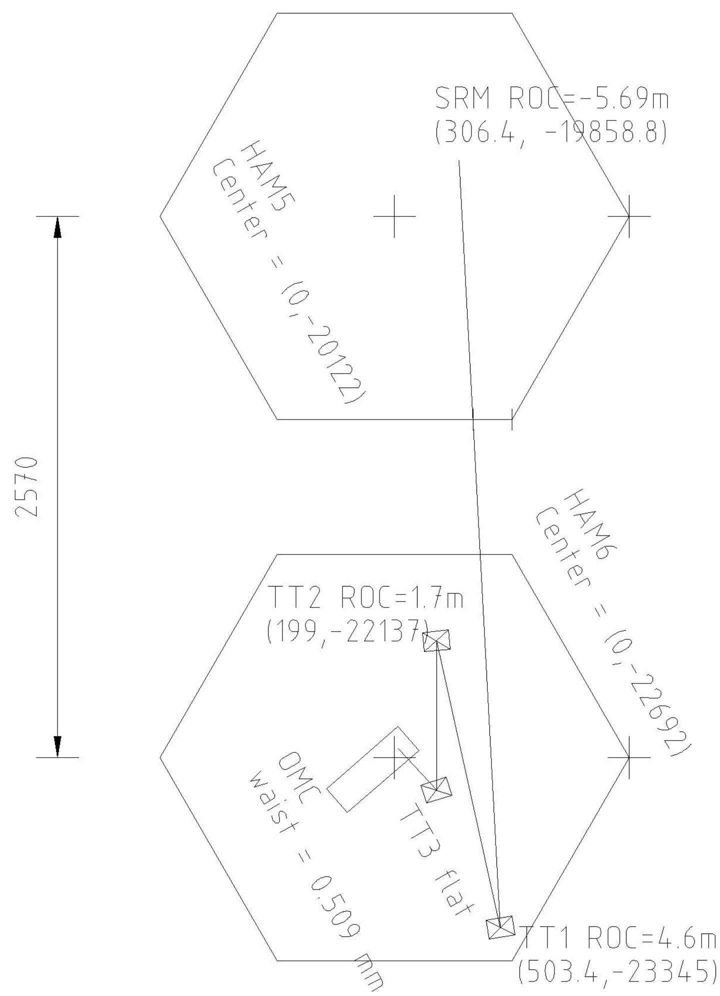

Figure 2: HAM5 and HAM6 layout.

4 References

1. LIGO-T0900043: “Optical Layout and Parameters for the Advanced LIGO Cavities”

2. LIGO-D0901920: “Advanced LIGO H1 Optical Layout, ZEMAX”

3. LIGO-T1000276: “Output Mode Cleaner Design”

4. `http://ilog.ligo-wa.caltech.edu/ilog/pub/ilog.cgi?group=detector&date_to_view=05/06/2009&anchor_to_scroll_to=2009:05:06:19:59:03-kawabe` for angle and POS coupling.

5. `http://ilog.ligo-wa.caltech.edu/ilog/pub/ilog.cgi?group=detector&date_to_view=05/15/2009&anchor_to_scroll_to=2009:05:15:21:15:42-kawabe` for lateral/bounce coupling. This is a variation of angle coupling, though.