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LLO OMC Mode Matching

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1 Introduction

The mode matching into the Livingston OMC has been measured to be between 89% and 93% depending on the interferometer state [1] [2] [3] [4] [5]. We decided to look into improving it, if possible. With HAM6 open during the September 2009 commissioning break, we took advantage of the opportunity to do in situ beam scans. We made several, all of which looked at a single bounce beam off ITMY. Two represented the beam from a cold interferometer and were taken before and after TT1 for a consistency check [5] [6]. The others were taken with various amounts of TCSY heating to study the effect of different ITMY lenses [7].

The scope of this document is to present our understanding of the OMC mode matching for the cold interferometer state. I use the data from the cold beam scans to construct a model of the OMC telescope. From this, I determine the best solution for improving the mode matching given practical constraints. We made the suggested changes during the week of Sep. 14. The results are summarized in Table 1 which compares the measured and modeled OMC mode matching numbers for before and after the telescope change.

Table 1: OMC Mode Matching

	Modeled	Measured
Before TT change	97.5%	$91 \pm 2\%$
After TT change	99.0%	$95 \pm 1\%$

An improvement in mode matching is desirable not only because it will increase the power throughput of the OMC, but it will reduce the coupling to junk light. We are, in effect, anti-mode matching to non-optical gain carrying carrier. This will improve the effectiveness of the OMC alignment servo.

2 Measurements

To do the beam scans we used an Omega Meter which quotes a ±5.0% error on diameter readings [8]. We had ETMY, ITMX and the RM misaligned so that the beam we were measuring was a single bounce off ITMY. We requested 1W input power to the mode cleaner and attenuated the resulting 3.75 mW beam on HAM6 with an ND filter. This reduced its power to 0.35 mW, within the range of the Omega Meter requirements.

There are three tip tilts, TT0, TT1, and TT2, that guide the beam from HAM4 into the OMC. We made one set of beam diameter measurements before the beam reaches TT1 and another set after it is reflected off of TT1. To make the work easier, we moved TT0 out of the way for the first set and TT2 out of the way for the second.

The data is presented in Table 2 and corresponding plots in Fig. 1. All locations are

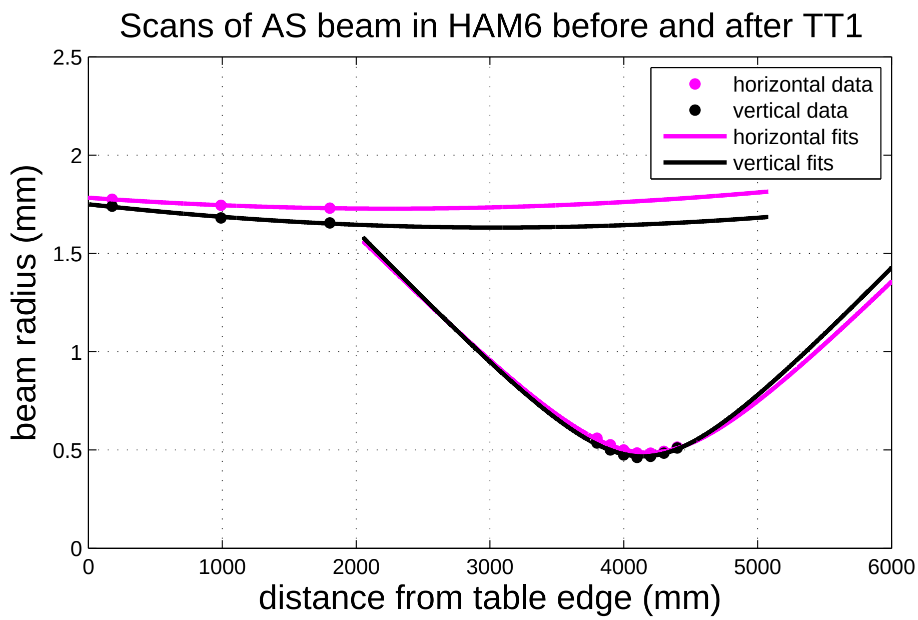

Figure 1: Beam scan data and fits.

referenced to the front edge of the table and represent distance along the beam path.

Table 2: Beam scan data

	location (mm)	vertical waist diameter (mm)	horizontal waist diameter (mm)
Before TT1	178	3.480	3.550
	991	3.360	3.490
	1803	3.310	3.460
After TT1	3800	1.070	1.120
	3900	1.000	1.052
	4000	0.950	1.000
	4100	0.925	0.970
	4200	0.935	0.968
	4300	0.968	0.985
	4400	1.020	1.030

The data show that the beam is astigmatic. I therefore had to create fits for two different beam profiles. From here on out, we will treat the horizontal and vertical beam profiles separately and combine their individual couplings to the OMC appropriately for final evaluation. Table 3 shows the parameters for the beam waists as found by a least squares fit in Matlab.

Table 3: Fits to beam scan measurements

		radius w_0 (mm)	location z_0 (mm)
Before TT1	horizontal	1.728	2253
	vertical	1.631	3046
After TT1	horizontal	0.486	4183
	vertical	0.468	4139

2.1 Choosing data to use

Unfortunately, the beam profiles do not meet up - the fit to the second set of data in Fig. 1 starts at the location of TT1. However, it's possible they are still consistent with each other within error bars; I just haven't calculated them. Since we took more data points for the second set and because we sampled the beam on both sides of the waist, its fit should be more accurate. For these reasons only, I'll choose this second set of data for use in my model. Upon propagating its beam profile backwards through TT1, we find a beam waist and location of the incident beam as outlined in Table 4.

Table 4: Incident beam parameters based on data after TT1

	radius w_0 (mm)	location z_0 (mm)
horizontal	1.534	3293
vertical	1.519	3975

3 Model

I proceed to use the beam parameters in Table 4 to create a complete model of the beam on HAM6. Figure 2 shows the layout of the table as of summer 2009. The baseline mirror locations and ROC used in the model are presented in Table 5.

Table 5: Initial parameters

optic	location (mm)	ROC (mm)
TT0	1016.0	∞
TT1	2057.4	5000
TT2	3860.8	4000
OMC input coupler	4165.6	∞

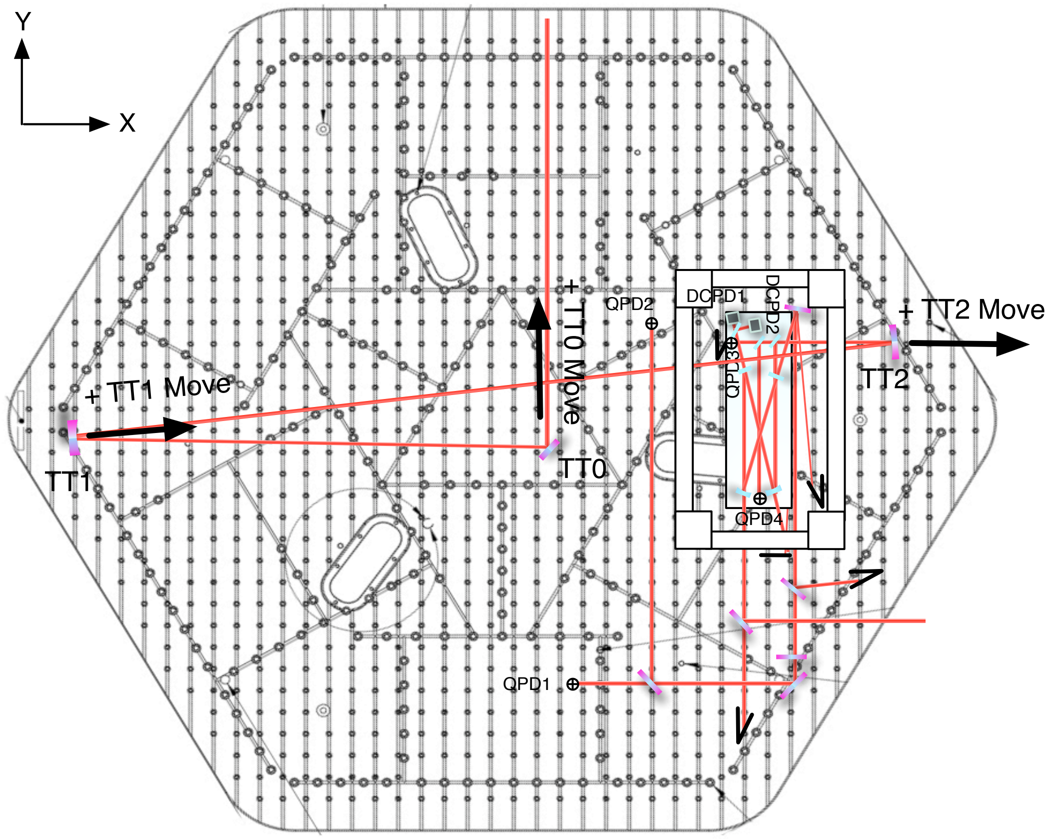

Figure 2: L1 HAM6 as of Sep. 11, 2009 before any mode match changes. The beam enters HAM6 at the top of the diagram and is steered into the OMC by TT0, TT1, and TT2. The arrows indicate the coordinate system used in considering changes in TT location. All changes are relative to their current locations. (Drawing courtesy of Jeff.)

The OMC geometric waist radius which is located at the input coupler is $\omega_{0_{cav}} = 0.465$ mm as reported by Sam [9]. In order to achieve perfect mode matching, the beam waist size and location must exactly match that of the OMC. The result of calculating the overlap integral, and therefore the percent of mode match, between two modes for each cross-section is given in St. Amant [10] as

$$P_x = P_y = \sqrt{\frac{4\sigma}{(\sigma+1)^2 + G^2}} \tag{1}$$

where $\sigma = (\frac{\omega_{o_{beam}}}{\omega_{0_{cav}}})^2$, $G = \frac{z_{0_{beam}} - z_{0_{cav}}}{z_{R_{cav}}}$ and z_R is the Rayleigh range. The total mode match is

$$P = P_x P_y \tag{2}$$

which ranges from 0 to 1.0.

There are four telescope parameters that we choose to change to maximize the mode matching. They are the TT1 and TT2 locations and their mirrors' radii of curvature (ROC). We do not include TT0 in this model in order to limit our parameter space.

4 Results

We make several contour plots, demonstrating how the mode matching is affected by changing two parameters at once. All plots will use sign conventions such that a '+' TT move is in the +x direction as indicated in Fig. 2. Blue stars on each contour plot indicate the maximum point. All data and plots take into account the astigmatism of the beam by calculating P as given in Eq. 2.

Figure 3 shows a calculation of the mode matching using the installed ROC of $R_1 = 5$ m and $R_2 = 4$ m mirrors for a large space of TT movements. We see that as is, at $\Delta TT1 = \Delta TT2 = 0$, the mode matching is predicted to be 97.5% and that perfect mode matching can be achieved by moving TT1 -432 mm and TT2 -102 mm. However, given the current table layout and its limitations, the best that can be done is to move TT2 to the edge of the table, achieving 98.6% mode matching.

Next we look at how good we can make the mode matching if we don't move the TTs, but instead change their mirrors' ROC. Figure 4 shows that $R_1 = 3.1$ m and $R_2 = 0.9$ m would provide an excellent 99.9% mode match. However, we should also note that there is a second local maximum in the direction of large R_2. Exploring contour plots (not shown) that include more data to the right, I find the maximum is always at the boundary. I conclude $R_1 = 5$ m and $R_2 = \infty$ might be a good solution and calculate that it indeed also provides a 99.9% mode match.

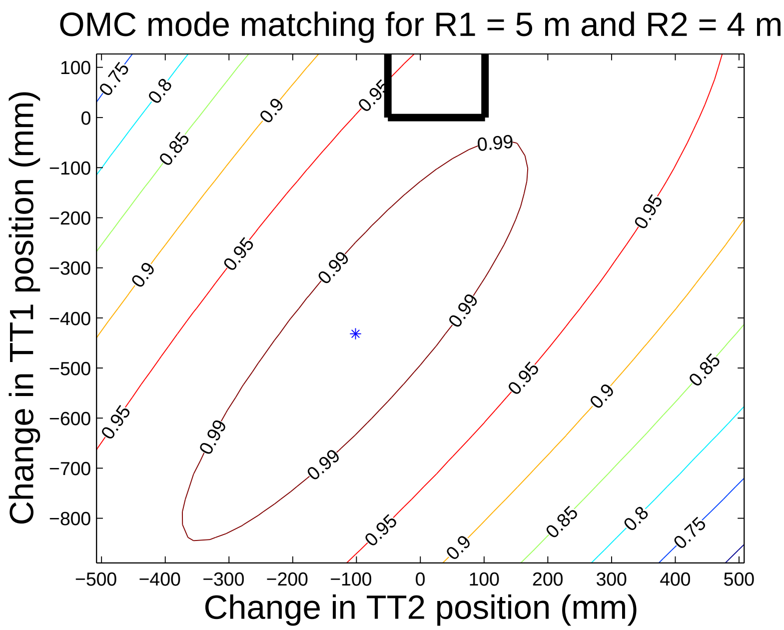

Figure 3: Space of TT positions for initial ROCs, R1 = 5m and R2 = 4m. 100% mode matching can be achieved by moving TT1 -432 mm and TT2 -102 mm. However, table constraints limit the realistic possibilities to within the black box. The best that can be done is to increase mode matching from 97.5% to 98.6% by moving TT2 102 mm (to the edge of the table).

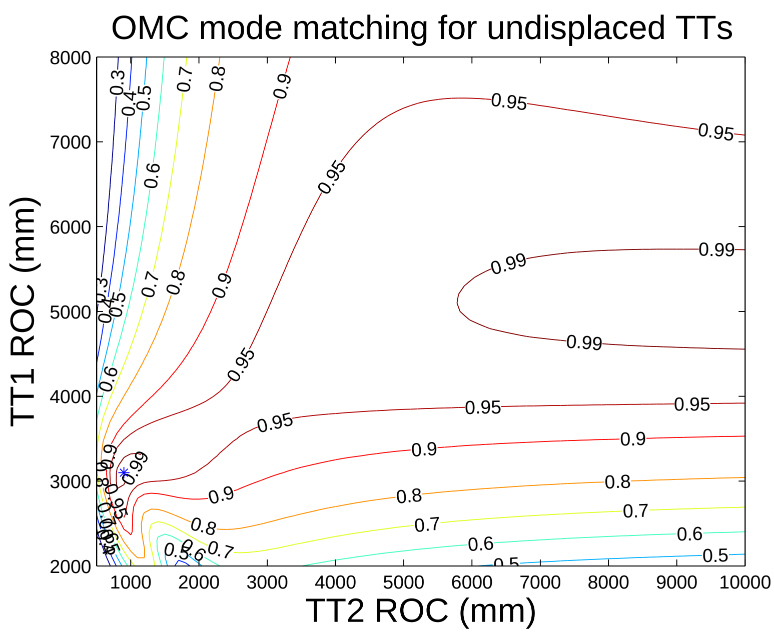

Figure 4: Radius of curvature space for the initial tip tilt positions. There are two 99.9% maximums. One is at R1 = 3100 mm and R2 = 900 mm. The other is at R1 = 5 m and R2 $= \infty$.

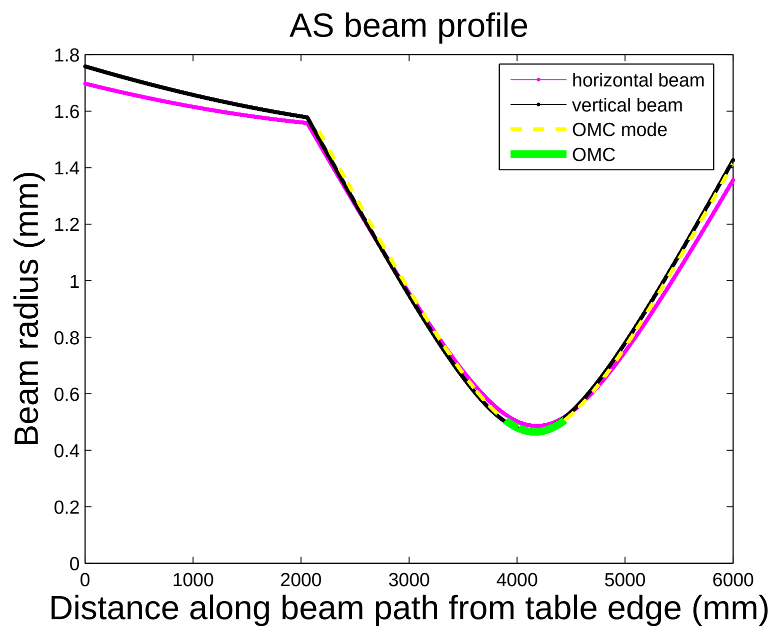

Figure 5: Beam profile on HAM6 for the telescope solution of R1 = 5 m, R2 = ∞. The OMC mode is shown in yellow with the green line depicting the actual size of the OMC. Mode matching is 99.9%.

5 The solution

Of the options presented above, we choose the $R_1 = 5$ m and $R_2 = \infty$ solution. For one, it yields nearly perfect mode matching *without* requiring any tip tilts to be moved. Secondly, it's more attractive than the $R_1 = 3.1$ m and $R_2 = 0.9$ m option because it uses easily attainable optics and is far less sensitive to errors in ROC.

Figure 5 shows the horizontal and vertical AS beam profiles that result from propagating the measurement parameters in Table 4 through the proposed TT telescope. The red and yellow-dashed lines show the mode of the OMC. Mode matching is 99.9%.

6 OMC MMT changes

We changed the OMC mode matching telescope between Sep 14 and 16. We replaced the TT2 optic with a CVI flat mirror coated for a 0 degree angle of incidence. However, other plans included placing black glass beam dumps behind the TTs. Since TT1 was already at the edge of the table, we had to move it 125 mm closer to the center in order to fit a dump behind it as shown in Fig. 6. We did not have to move TT2. The model predicts a 99.0% mode match into the OMC based on these actual changes.

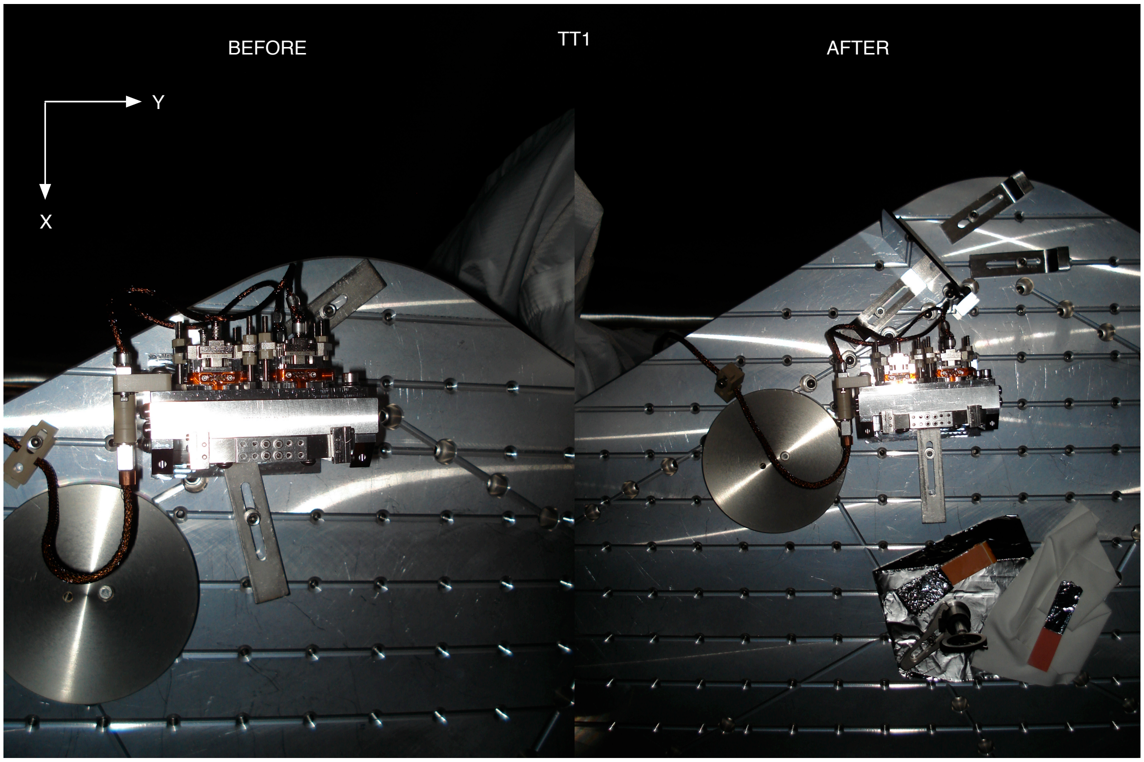

Figure 6: TT1 before and after positions.

7 Conclusion and future work

Once HAM6 was returned to vacuum after our changes, we measured the OMC mode matching to be about 95% for a single bounce in a cold interferometer state [11] [12]. The improvement of about 4% is not bad. It's hard to say though what we actually expected given the large discrepancy between the measured and modeled initial data.

Contamination of higher order modes in the incident beam would contribute to a decreased visibility, but a mode scan proves that only the misalignment TEM01 and TEM10 modes may have a significant presence [12]. Impedance mismatch due to cavity losses would have the same effect, but Tobin has calculated it to be only 0.06% of the input power. Tobin has also estimated the M^2 quality factor of the beam to be 1.1 - 1.2 [7]. Further analysis would be required to determine the beam quality's effect on visibility measurements.

Jeff is working on a model to make predictions as to how the mode matching is affected by heated ITMs. Nic has calculated the Gouy phase separation of the TTs for evaluation of angular control and has also estimated their beam jitter sensitivity [13].

References

[1] Matt Evans. LLO elog, July 14, 2009.

[2] Tobin Fricke. LLO elog, June 9, 2009.

[3] Valera Frolov. LLO elog, September 8, 2009.

[4] Tobin Fricke. LLO elog, July 6, 2009.

[5] Tobin Fricke. LLO elog, September 11, 2009.

[6] Kate Dooley. LLO elog, September 3, 2009.

[7] Tobin Fricke. LLO elog, September 14, 2009.

[8] Inc. THORLABS. Operating manual model wm100 and wm100b omega meter beam profiler. Technical Report Doc. No. 0224-D05, August 2005.

[9] S. Waldman. The enhanced ligo output mode cleaners. Technical Report LIGO-T080144-00-I, February 2009.

[10] D. Gariépy Y. St-Amant and D. Rancourt. Intrinsic properties of the optical coupling between axisymmetric gaussian beams. *Applied Optics*, 43(30):5691–5704, October 2004.

[11] Valera Frolov. LLO elog, September 18, 2009.

[12] Kate Dooley. LLO elog, September 24, 2009.

[13] Nicolas Smith. LLO elog, September 11, 2009.