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Mode Mismatch Analysis for LLO

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1 Introduction

1.1 Purpose

This document analyzes the mode mismatch at LLO. Particularly data from beam width measurement by Valera Furlov in 2003 and recent reflected power data is analyzed to determine the mode matching at LLO. We also propose adjustments to MMT_2 position for mode matching improvements.

1.2 Scope

This document is prepared for mode mismatch analysis at LLO and proposes using some tests to further analyze the interferometer for e-LIGO. Typical readers of this include people involved in designing core optics, input/output system, and thermal compensation system.

1.3 Definitions

1.4 Acronyms

IMC: Input Mode Cleaner

MMT: Mode Matching Telescope

NRSB: Non-Resonant Side Band

TCS: Thermal Compensation System

1.4.1 LIGO Documents

1. Muzammil A. Arain and Guido Mueller, “Bullseye Detectors for Mode Matching Measurements for e-LIGO,” LIGO- T070120-00-Z.

1.4.2 Non-LIGO Documents

2. Valera Furlov, ILOG entry, Januray 3, 2003, http://ilog.ligo-la.caltech.edu/ilog/pub/ilog.cgi?group=detector&task=view&date_to_view=01/03/2003&anchor_to_scroll_to=2003:01:03:13:26:33-valera.
3. Valera Furlov, ILOG entry, May 31, 2007, http://ilog.ligo-la.caltech.edu/ilog/pub/ilog.cgi?group=detector&task=view&date_to_view=05/31/2007&anchor_to_scroll_to=2007:05:31:22:49:28-valera.
4. Guido Mueller, G. Mueller, “Modematching measurements February 2007”.

2 General Description

The mode matching between the Input Mode Cleaner (IMC) and the main interferometer should be improved during the break between S5 and eLIGO. The reflected field at LLO shows a Bullseye structure. Recently Valera Furlov [2,3] measured the power at the reflected port as the interferometer acquires lock. His findings show that at 1 W, there is about 10% light at the reflected port. As the interferometer power is increased to 7 W, the reflected power increases to 17%. These measurements suggest that the mode matching at LLO should be improved. One source of this reflected power may be the mode matching telescope parameters between the IMC and the IFO. However this can only explain 10% of the mismatch at low power. The remaining 7% mode mismatch source is power dependent, and so probably due to thermal effects or radiation power effects. In this note we will try to analyze the situation based upon the available measurements.

3 Beam Scan Measurements

Ref 2 describes beam width measurement at the reflected port. Fig. 1 shows graph from the ilog entry.

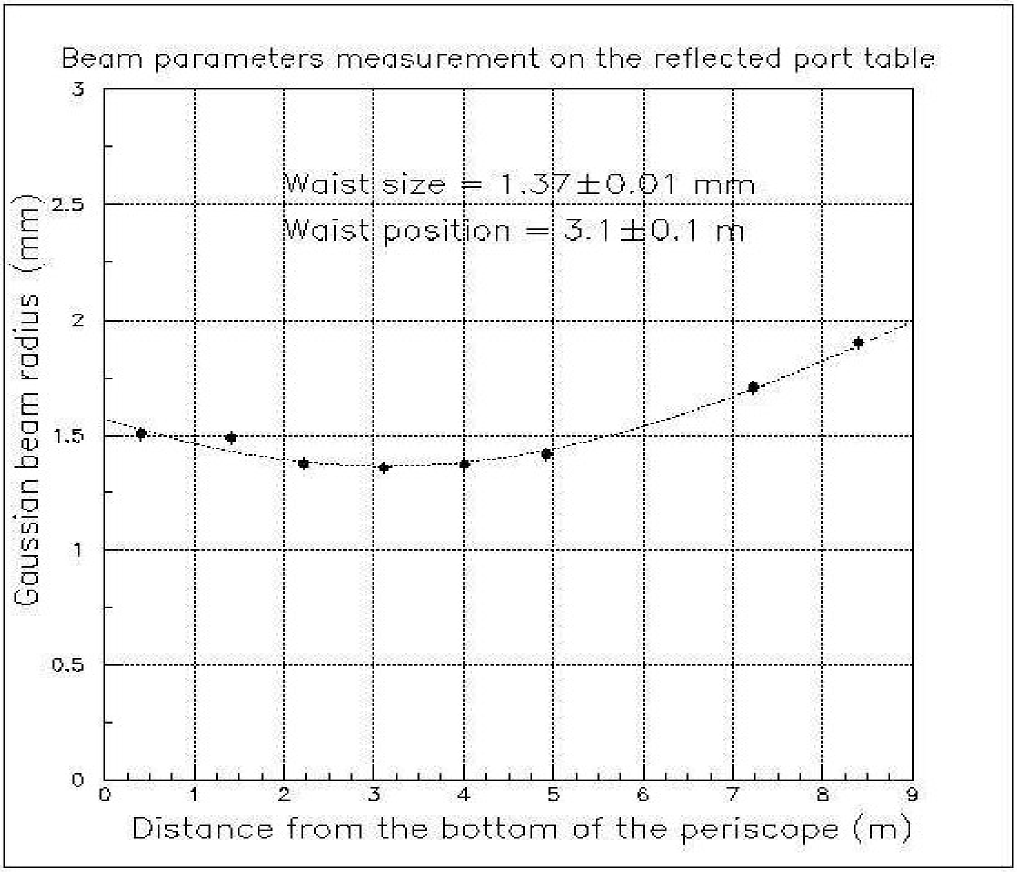

Fig. 1: Beam scan data for the beam reflected from PRM at low power.

These measurements were performed when the arm cavities were misaligned and the light was reflected from the recycling mirror. Therefore, this beam passes through all the optics from IMC to PRM twice. On its way back, the pick-off from the FI is transmitted through the view port and the beam width measurements are done. Using parameters given in Ref. 4, we try to reconstruct the mode as a function of MMT_2 displacement from a reference position. The resultant mode after propagating the beam from IMC to the PRM amd from PRM back to view port through FI is then used to evaluate an overlap integral with the measured mode as shown in Fig. 2 for various positions of MMT_2. Note that mode matching is very sensitive to the distance between MMT_2 and MMT_3. Moving MMT_2 provides a convenient way to model ROC errors and positioning errors.

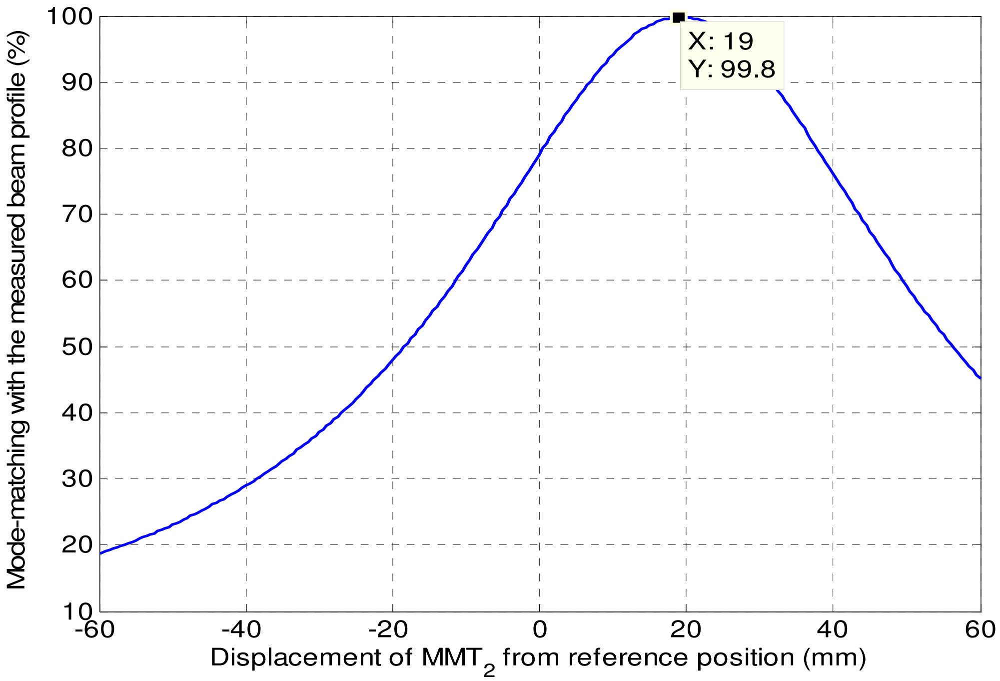

Fig. 2: Overlap between the simulated and the measured data for various positions of MMT$_2$ mirror.

From Fig. 2, the relative position of MMT$_2$ that provides the maximum overlap with the measured mode in Fig. 1 can describe the current optical layout. Here the mode overlap is calculated between the measured mode and the simulated mode calculated with different positions of MMT$_2$. If we calculate the mode by displacing MMT2 by 19 mm from the design position, we get an overlap of 99.8% between the simulated mode and the measured mode. In Fig. 2, the reference position of zero is selected such that it gives the maximum mode matching into the IFO as shown in Fig. 3 and thus corresponds to the design value.

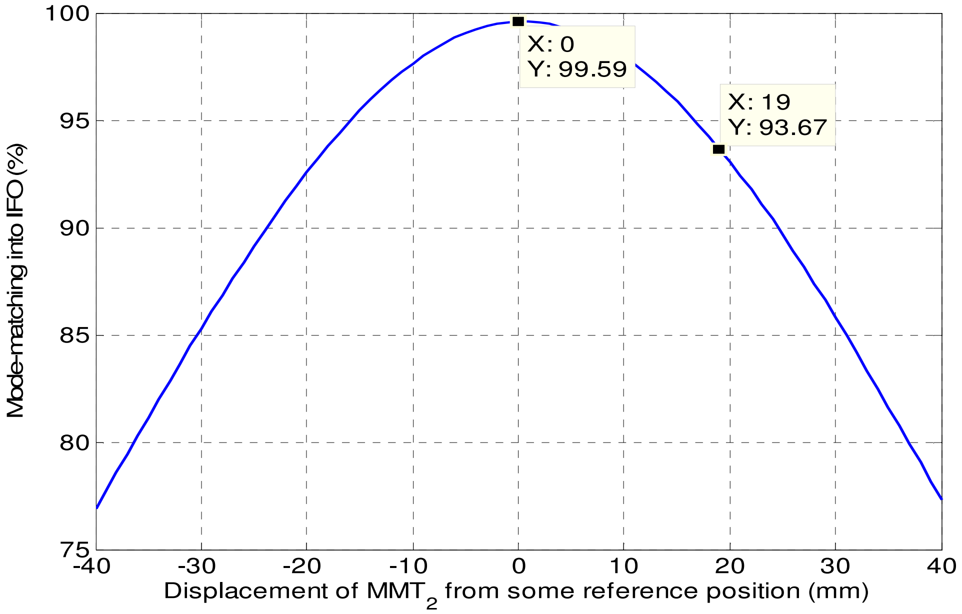

Fig. 3:Mode matching into IFO as a function of MMT_2 position. The reference position corresponds to a distance of 14.448 m distance between MMT_2 and MMT_3.

Fig. 3 shows the optimal coupling is obtained when the distance between MMT_2 and MMT_3 is 14.448 for the nominal values of ROCs. In practice, this should be different, on account of the actual ROC of the mode matching telescope mirrors. However the important point is the difference between the optimal position of MMT_2 in Fig. 2 and Fig. 3. The difference between the two positions tells us how much we should move MMT_2. This result is 19 mm as shown in Fig. 2. So for optimal mode matching into the distance between MMT_2 and MMT_3 should be decreased by 19 mm. Also a relative displacement of 19 mm from the optimal point results in about 6% mode mismatch. However Ref. 2 and 3 suggest that there is about 10% mode mismatch at low power.

It could be the case that the beam width measurements were carried out in January 2003 while the power data is current. So the optics might have been displaced since then. This suggests that it is very desirable to repeat these measurements afresh. Another explanation could be that the remaining 6% mode mismatch is due to impedance mismatch.

4 Analysis of recent reflected power measurements

Recent work from Valera can be summarized in the following graph.

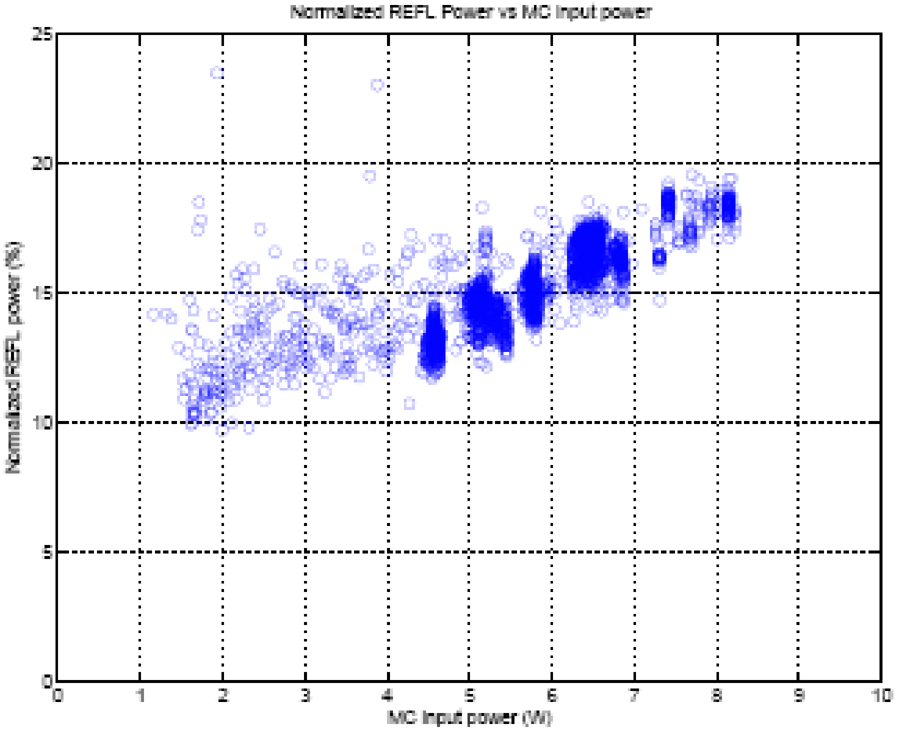

Fig. 4: Normalized reflected power as a function of MC input power. The data is for last 500 days.

Fig. 5 shows that at low power mode mismatch is about 10%. After that it increases linearly with a slope of about 1% per Watt. At the proposed 35 W, this could translate into as much as 35% mode mismatch. The source of this power dependent mode mismatch could be thermal lensing in the Faraday isolator, , thermal lensing in other optics, alignment wedging etc. For the purpose of this analysis we assume that this effect is due to thermal lensing. There could be two sources of thermal lensing: the FI and ITM substrate.

4.1 Thermal Lens in FI

First we analyze the effect of thermal lensing in FI on mode matching. Here we use the model developed earlier where displacement of MMT_2 can be used to model an initial mode mismatch.

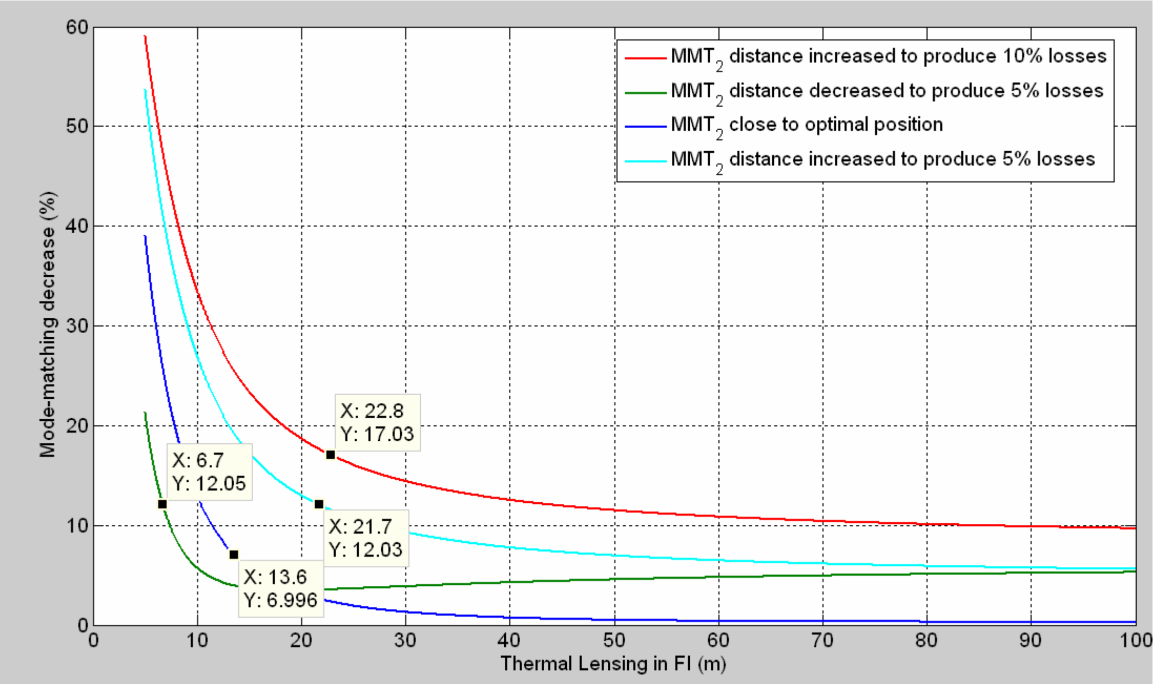

Fig. 5: Mode mismatch as a function of thermal lensing in FI for various MMT_2 positions. The blue curve corresponds to the optimal point where more than 99.5% light is coupled into the IFO.

Here as mentioned earlier, we start with a mode mismatch of 10% Out of this about 6% could be due to incorrect MMT_2 positioning. It is important to note that if the distance between MMT_2 and MMT_3 is shorter than expected, any thermal lens in the FI will actually improve the mode matching. However this is clearly not the case and therefore this also asserts that the distance between MMT_2 and MMT_3 needs to be decreased. The correct value for this distance can be confirmed if we made a current beam width measurement at the reflected port. The red and cyan curves indicate that if the mode mismatch due to MMT_2 position is between 5-10 %, an additional 7% mode mismatch will be created for a thermal lens of about 20-25 m focal length thermal lens in FI at full power. However the measured focal length for the FI at full power was 60 m at full power of 8 W.

4.2 Thermal Lens in ITM Substrate

Next we do the same analysis for a lens in ITM substrate. This lens could be due to ITM surface/substrate absorption or could be due to TCS operation. It is important to note that the TCS does not keep the mode of the arm cavity constant instead it tries to improve the coupling between carrier and resonant side band.

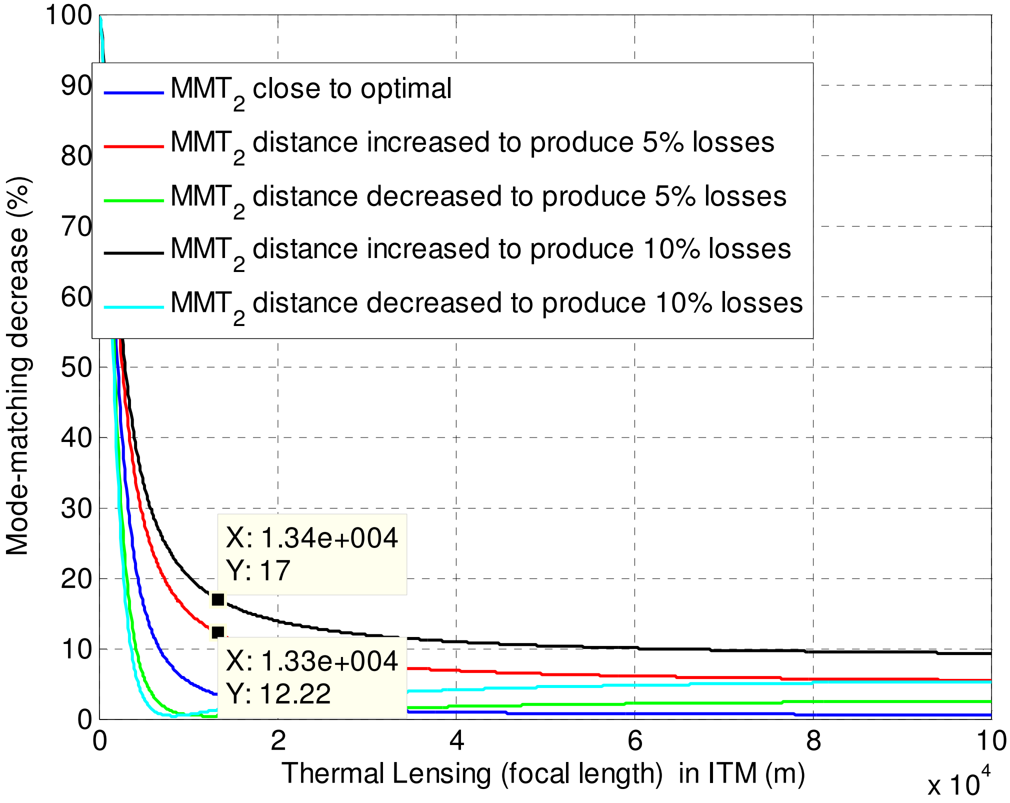

Fig. 6: Mode mismatch as a function of thermal lensing in ITM substrate for various MMT$_2$ positions. The blue curve corresponds to the optimal point where more than 99.5% light is coupled into the IFO.

Fig. 6 shows that any thermal lensing in ITM substrate would also have improved the mode matching in IFO if MMT$_2$-MMT$_3$ distance were too short. Moreover, an increase of 7 % reflected power at full power could be due to a thermal lens of 13-14 km in the ITM substrate. For a beam of 3.6 cm this corresponds to a sagitta change of 50 nm. Absorbed power of about 100 mW would produce such a thermal lens. For 26 kW power in the arm cavity, this means ITM coating absorption of 3.5 ppm can produce such a thermal distortion. (In practice, this could be a combination of both coating absorption and substrate absorption.) Another important factor is application of TCS annular ring pattern heating to the ITM. It could be that the coating absorption is quite high in ITM substrate but TCS annular heating pattern is reducing the thermal lensing in ITM substrate by creating a negative thermal lens. The 13 km thermal lens may very well be such residual thermal lensing.

5 Summary

In summary, the available data (Valera's beam scan measurement from 2003) suggest strongly that the distance between MMT$_2$ and MMT$_3$ should be decreased by 20 mm. However, this measurement should be repeated to check the current situation.

If the extra 7% power-dependent loss as measured by Valera is from thermal lensing in the system, it could be either due to a thermal lens of 20 m in FI or a 13 km residual thermal lens in ITM substrate. However, it is important to investigate further the source of this mode mismatch.

6 To Probe Further

To further confirm these investigations, we propose the following:

1. A new set of beam scan measurements should be done at low power as well as high power. This will show if there is any thermal lensing problem in the FI or not. This will also tell us how much we are mode mismatch from the IFO beam to some extent.
2. Power data at reflected port should be analyzed at very low power of the TCS. If mode mismatch increases at any power level after removing the annular heating at the ITM substrate, it will confirm that the 7% mode mismatch is due to thermal lensing in the ITM.
3. At the same time, a Bullseye measurements at full power will be helpful in understanding the behavior of recycling and arm cavities at full power.
4. Finally to confirm the need for MMT_2 repositioning, Bullseye (or beam width) measurements be performed by using HEPI to control the distance between MMT_2 and MMT_3.
5. The new FI should be tested in vacuum for thermal lensing and this should be used to evaluate the effect of new FI on mode matching.