LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T030006-00-D *LIGO* 01/14/03

Errant Beam Analysis, LIGO1

Michael R. Smith

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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/

Table of Contents

Table of Tables

Table of Figures

Abstract

1 Introduction

1.1 Background

On 6/28/02 the suspension wire for the MMT2 suspended optic in the 2 km interferometer (H2) at the LIGO Hanford Observatory failed. An investigation (LIGO-T020116-00) concluded that instability of the SM2 suspension controller caused the laser beam to impinge upon and heat the MMT2 suspension wire, causing catastrophic failure of the wire.

1.2 Scope

In this technical note, simple heat flow models are used to estimate the heating of suspension wires caused by errant laser beams directed by rogue mirrors and to identify the likely places where damage to suspension wires and OSEM control signals could occur.

Recommendations are made for placing baffles in order to eliminate the possibility of damage to suspension wires and OSEM control cables due to errant laser beams.

1.3 Referenced Documents

LHO 2K Suspension Wire Breakage Incident, LIGO-020116-00-W

Planned Response to the LHO 2K Suspension Wire Breakage Incident, LIGO-M020389-00-D

Report of Review Committee on the LHO 2K Suspension Wire Breakage Incident, LIGO-Mm020366-00-M

2 Analysis

2.1 Wire Heating Model

Two simple analytical models for the heating of the target mirror suspension wire are developed below, as an aid in identifying the critical errant beams. The first case applies to the continuous heating of the wire by the power of an errant laser beam. The second case applies to the pulsed heating of the wire by an errant laser beam from the stored energy in a resonant cavity that is misdirected by a rogue mirror.

The errant laser beam of diameter w impinges onto the suspension wire of the SOS mirror suspension structure as shown schematically in **Figure 1**.

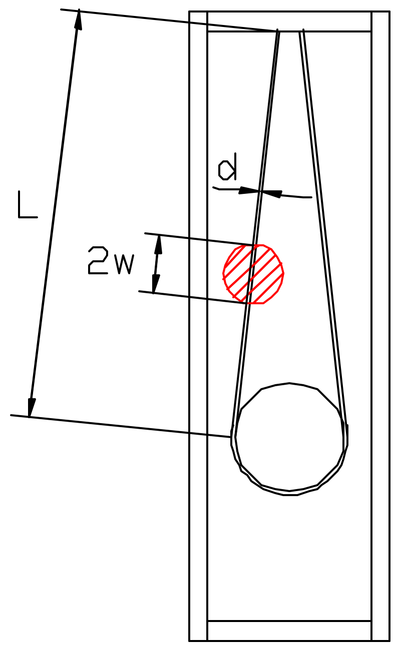


Figure 1: SOS Suspension Model

2.1.1 Continuous Heating Model

A one-dimensional heat conduction model will be developed to estimate the temperature rise of the wire due to the absorbed laser power, as shown in Figure 2. The model assumes that the extent of the laser-heating source is much smaller than the length of the conduction path. It also assumes that half the absorbed laser power Q flows away from the heat source in opposite directions through the cross section of the wire for a characteristic length L to an infinite reservoir at temperature T_0, raising the heated portion of the wire to a temperature T. The wire is in a vacuum, so there will be no heat convection from the surface of the wire. The heat loss due to radiation is ignored because of the relatively low temperatures involved.

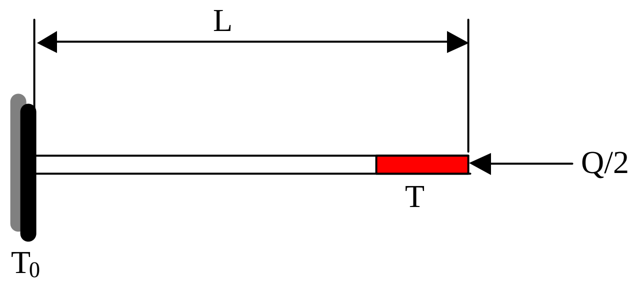


Figure 2: One-dimensional heat conduction model

The rate of heat conduction through the wire is given by the heat conduction equation,

$$\frac{Q}{2} = kA\frac{dT}{dx}$$

where k is the heat conduction coefficient, A is the cross-sectional area of the wire, and dT/dx is the thermal gradient along the wire.

We can integrate along the length of the heat conduction path to determine the temperature rise of the heated portion of the wire.

$$\Delta T = \frac{QL}{2kA}$$

The heating rate Q is equal to the amount of laser power absorbed by the wire,

$$Q = Ph(1-R)\frac{2wd}{pw^2}$$

where P is the laser power incident on the wire, ? is the fraction of time the laser dwells on the wire, R is the absorption coefficient of the wire surface, and w is the Gaussian beam parameter.

Substituting into the heat conduction equation, we can calculate the temperature rise of the heated portion of the wire.

$$\Delta T = Ph(1-R)\frac{4L}{p^2 kwd}$$

2.1.2 Pulsed Heating Model

If the laser energy E is absorbed in a sufficiently short duration, during which negligible heat has been conducted through the wire away from the heated portion, then the absorbed energy will be taken up by the heat capacity of the heated volume of wire and only the temperature of the heated portion will rise significantly,

$$E = mC_p\Delta T$$

where m is the mass of heated wire, and C_p is the heat capacity at constant pressure of the wire.

The mass of the heated portion of the wire is equal to

$$m = r\frac{pd^2}{4}2w$$

The energy absorbed by the wire is given by the expression,

$$E = P_s t_s (1-R)\frac{2wd}{pw^2}$$

where P_s is the pulsed laser power for a pulse duration t_s.

Then the temperature rise of the heated portion of the wire can be calculated.

$$\Delta T = \frac{4P_s t_s (1-R)}{p^2 r d w^2 C_p}$$

2.2 Absorbed Power, Laser Spot Size, and Absorbed Energy Density

The temperature rise of the continuously heated wire is proportional to the absorbed power and inversely proportional to the laser spot size. The temperature rise of the pulsed heated wire is proportional to the absorbed energy density (Joules/m^2). The calculations of these values will be described in the following.

2.2.1 Laser Spot Size

The laser spot size was determined at each target location by using the ABCD Gaussian beam propagation method starting with an appropriate beam waist at the 2K and 4K input mode cleaners.

2.2.2 Stored Energy in a Resonant Optical Cavity

The mode cleaner and the arm cavity are sources of stored laser energy that can be directed by a rogue cavity mirror onto a target site that resides within the cone of errant beams.

The power stored inside a resonant cavity that is pumped by a continuous laser of power P_0 is given by,

$$\frac{P_s}{P_0} = \left(\frac{t_1}{1-r_1 r_2}\right)^2$$

where t_1 is the transmission coefficient of the input mirror of the cavity, r_1 and r_2 are the reflection coefficients of the input ant output mirrors respectively.

The storage time of the cavity is the duration of time during which most of the stored energy will exit the cavity when the cavity looses lock, e.g. if one of the cavity mirrors is suddenly steered away from the resonant condition,

$$t_s = \frac{L_c F}{cp}$$

where L_c is the full length of the cavity, c is the speed of light, and F is the finesse of the cavity, given by the following expression.

$$F = \frac{p\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

2.3 Angular Range of Errant Beams from Rogue Mirrors

The rogue mirrors are suspended inside either an SOS (small optics) suspension structure or a LOS (large optics) suspension structure. The following assumptions are made regarding the range of motion that the mirrors are allowed to make before being restricted by the earthquake stops:

SOS

Diameter of mirror	75 mm
Spacing between mirror and earthquake stop	1 mm
Mirror deviation half-angle	T_M = 1/35 = 0.029 rad = 1.6 deg
Beam deviation half-angle	T_B = 2 x 1.6 = 3 deg

LOS

Diameter of mirror	250 mm
Spacing between mirror and earthquake stop	1 mm
Mirror deviation half-angle	T_M = 1/125 = 0.008 rad = 0.46 deg
Beam deviation half-angle	T_B = 2 x 0.46 = 0.9 deg

Therefore, it was assumed that a rogue SOS mirror could spray a cone of errant beams with a 3 deg half-vertex angle, and a rogue LOS mirror could spray a cone of errant beams with a 0.9 deg half-vertex angle.

2.4 Identification of Target Sites

2.4.1 2K Interferometer

2.4.1.1 2K IO Section

The potential target sites of the errant beams in the IO section were identified by superimposing a 3 deg half-vertex angle cone on several rogue mirrors of the plan view LHO integrated layout drawing of the 2K IFO, as shown in Figure 3.

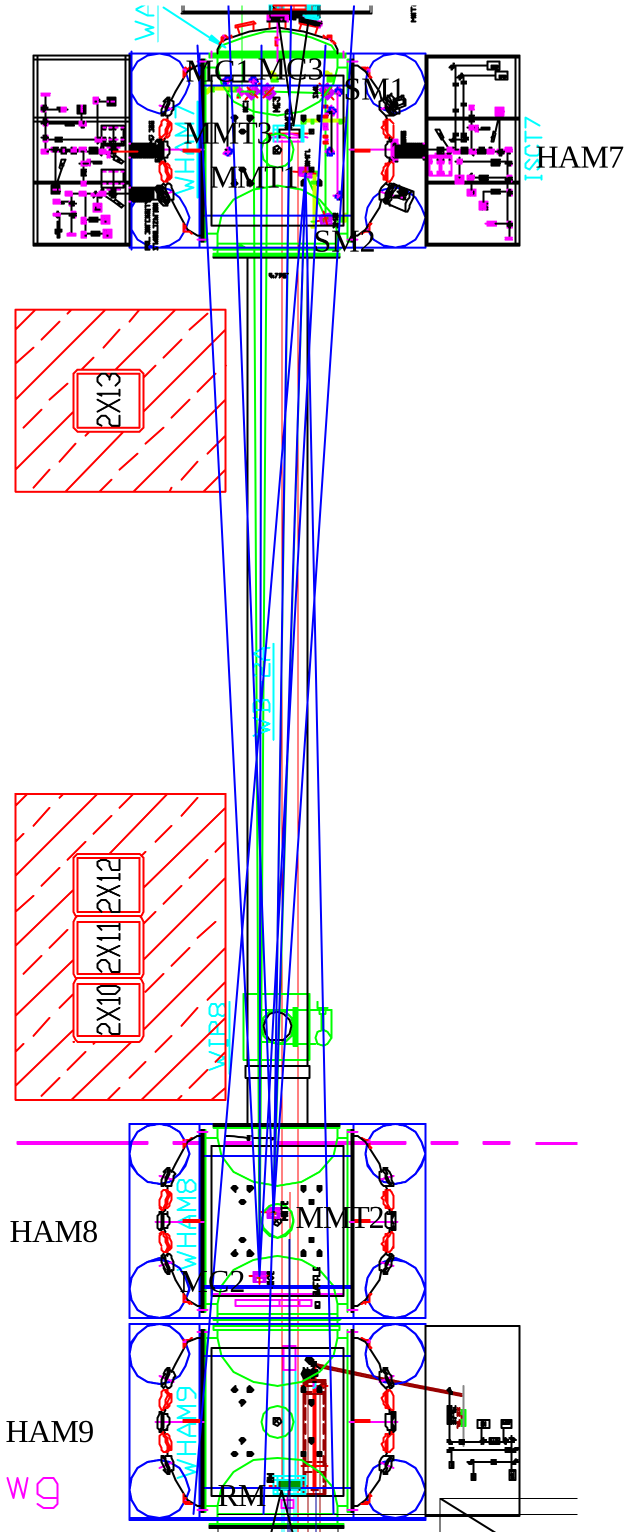


Figure 3: 2K IFO IO Section Rogue Mirrors

It is apparent from the ACAD drawing of the 2K IFO that the MMT2 rogue mirror is capable of spraying errant beams onto the MC1, MC3, SM1, SM2, MMT1, and MMT3 suspension structures.

The MMT1 rogue mirror is capable of spraying errant beams onto the MMT2, MC2, and RM suspension structures. The IO baffle does not quite block the errant beams from hitting the RM suspension wires, as shown in Figure 4.

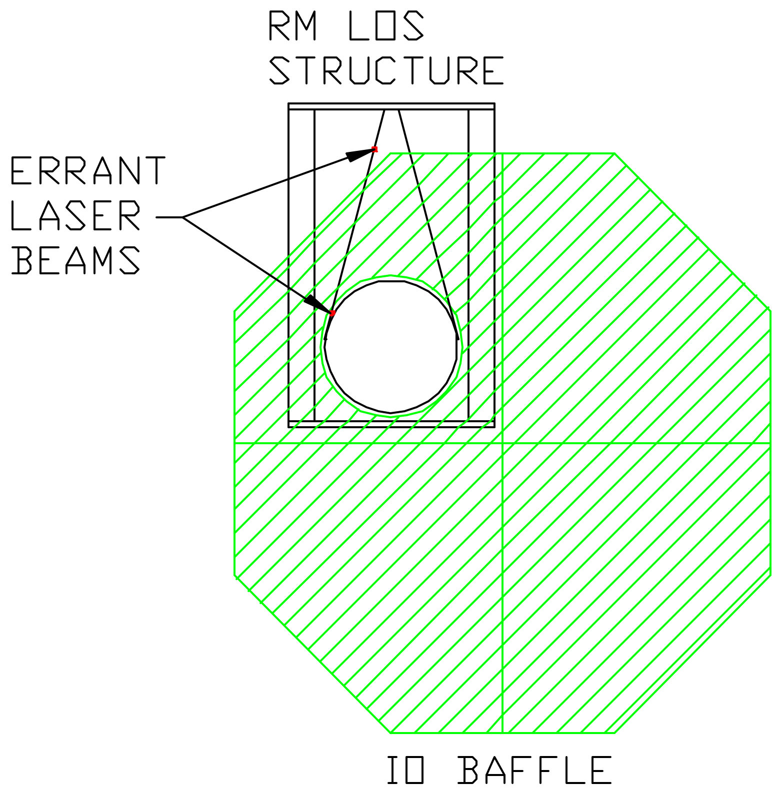
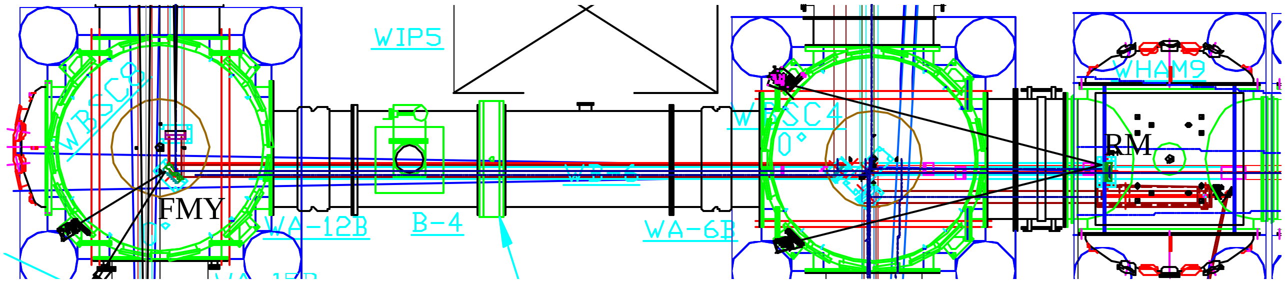


Figure 4: IO Baffle and RM LOS Structure

The MC2 rogue mirror is capable of spraying errant beams onto the MC1, MC3, SM1, MMT1, and MMT3 suspension structures

2.4.1.2 2K Recycling Cavity

The potential target sites of the errant beams in the recycling cavity were identified by superimposing a 1 deg half-vertex angle cone on the RM and the BS of the plan view LHO 2K IFO integrated layout drawing.



BSC8 BSC4 HAM9

Figure 5: 2K RM Rogue Mirror

2.4.1.2.1 2K RM

From the ACAD drawing of the 2K IFO, shown in

Figure 5, it can be seen that the 2K RM rogue mirror is capable of spraying errant beams onto the 2K FMy.

2.4.1.2.2 2K BS

From the ACAD drawing of the 2K IFO, shown in Figure 6, it can be seen that the 2K BS rogue mirror is capable of spraying errant beams onto the 2K FMx.

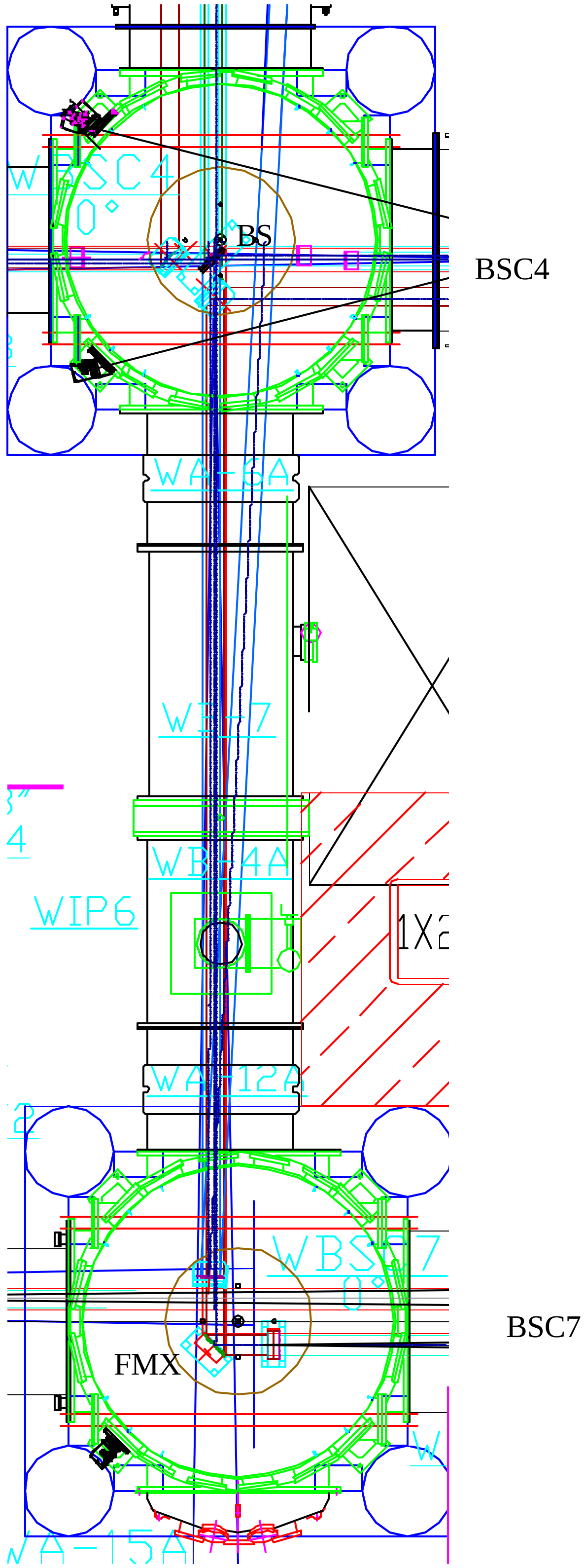


Figure 6: 2K BS Rogue Mirror

2.4.1.3 2K Arm Cavity

The 2K ETM rogue mirrors are capable of spraying errant beams onto the 2K ITM and 2K FM mirrors.

2.4.2 4K Interferometer

2.4.2.1 4K IO Section

The potential target sites of the errant beams in the IO section were identified by superimposing a 3 deg half-vertex angle cone on several rogue mirrors of the plan view LHO integrated layout drawing of the 4K IFO, as shown in Figure 7. From the ACAD drawing of the 4K IFO it can be seen that the MMT2 rogue mirror is capable of spraying errant beams onto the MC1, MC3, SM1, MMT1, and MMT3 suspension structures; the MMT1 rogue mirror is capable of spraying errant beams onto the MMT2, MC2, and RM suspension structures; and the MC2 rogue mirror is capable of spraying errant beams onto the MC1, MC3, SM1, MMT1, and MMT3 suspension structures

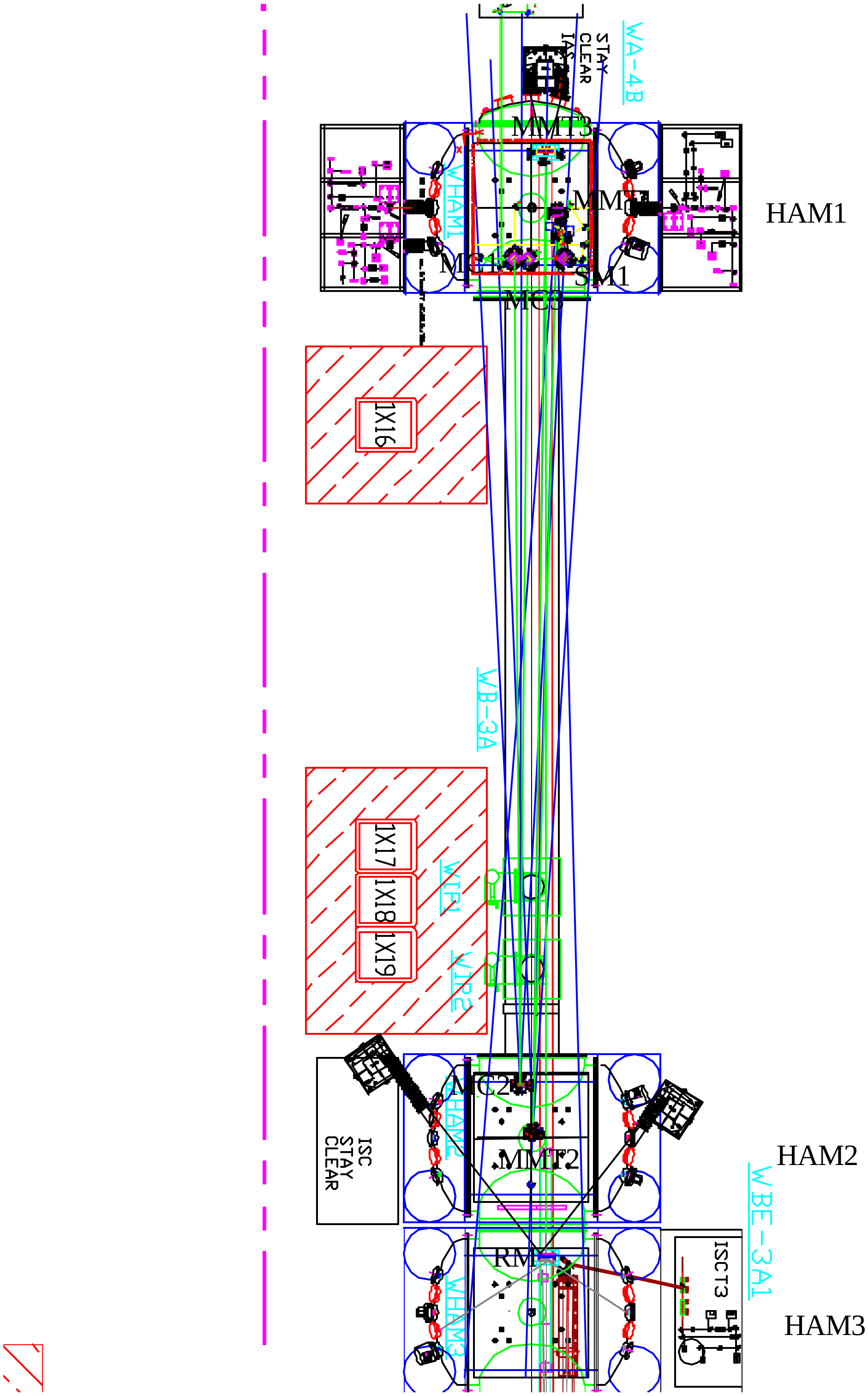
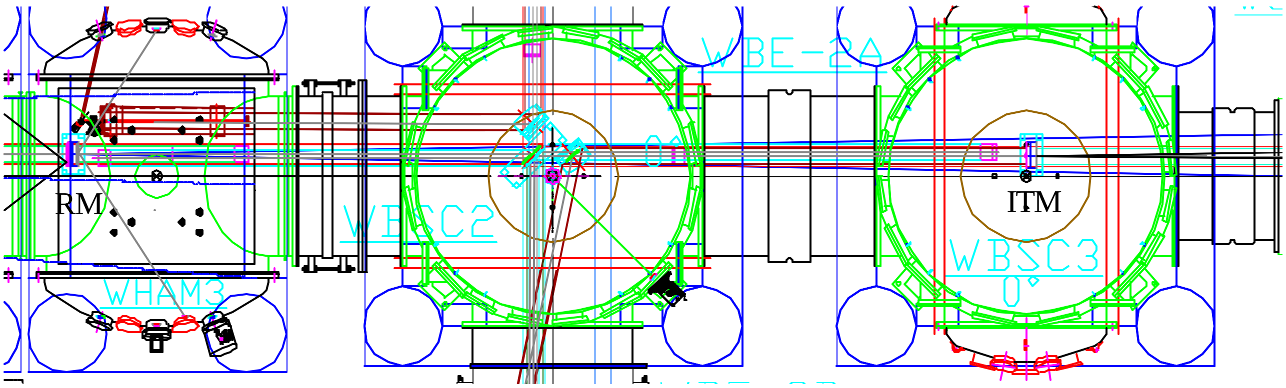


Figure 7: 4K IFO IO Section Rogue Mirrors

2.4.2.2 4K Recycling Cavity

2.4.2.2.1 4K RM

From the ACAD drawing of the 4K IFO, shown in Figure 8, it can be seen that the 4K RM rogue mirror is capable of spraying errant beams onto the 4K ITM mirrors. However, the ITM mirror suspension wires are shielded from the errant beams by the elliptical baffles mounted to the ITM mirrors facing the 4K RM.



HAM3 BSC2 BSC3

Figure 8: 4K RM Rogue Mirror

2.4.2.3 4K Arm Cavity

The 4K ETM rogue mirrors are capable of spraying errant beams onto the 4K ITM mirrors.

3 Results of Temperature Calculations

3.1 Parameters for Temperature Calculations

The temperature calculations for the target suspension wires in the 2K and 4K interferometers are based on the parameters shown in Table 1. A heating duty cycle of 5% is arbitrarily chosen for the continuous heating case. For the pulsed heating case, it is assumed that a random event could occur that enables the errant beam to dwell on the suspension wire during the discharge time of the optical cavity.

Table 1: Heating Calculation Parameters

LASER POWER	6	WATT
t1, arm cavity	0.173	
r1, arm cavity	0.985	
r2, arm cavity	1	
ARM CAVITY STORED POWER	20000	WATT
ARM CAVITY STORAGE TIME	9E-04	SEC
ARM CAVITY STORED ENERGY	17.5	JOULE
RC STORED POWER	300	WATT
RC STORED ENERGY	7.50E-04	JOULE
RC STORAGE TIME	2.50E-06	SEC
t1, mode cleaner cavity	0.0447	
r1, mode cleaner cavity	0.9988	
r2, mode cleaner cavity	0.9988	
2K MODE CLEANER BEAM WAIST	1.818	mm
4K MODE CLEANER BEAM WAIST	1.629	mm
MODE CLEANER STORED POWER	9055	WATT
MODE CLEANER STORAGE TIME	5E-05	SEC
MC STORED ENERGY	0.45	JOULE
SOS WIRE DIA	0.0000432	m
LOS WIRE DIA	0.0003048	m
DENSITY	7900	KG/m^3
WIRE REFLECTIVITIY	0.7	
SPECIFIC HEAT	450	J/KG*K
WIRE LENGTH	0.2	m
HEATING DUTY CYCLE	0.05	
HEAT CONDUCTION COEFF.	80	W/m*K

3.2 2K IFO Suspension Wire Temperature Rise

The calculations of the temperature rise of various target suspension wires in the 2K IFO are shown in Table 2.

- MMT1 is the most destructive rogue mirror. Its errant beams may cause the highest temperature rise of suspension wires at the target locations of MMT2, MC2, and the RM.

- The stored energy in the mode cleaner may be a problematic source of errant energy at the target locations of MC1, MC3, MMT3, MMT1, and SM2.
- MMT2 is a marginally problematic rogue mirror with errant beams at the target locations MC1, SM2, and MMT3.
- The errant stored energy in the arm cavity appears to be relatively benign, because of the low energy density associated with the large spot size at the ITM location.
- The errant stored energy in the recycling cavity is also negligible because of the relatively low finesse and the short storage time. CW heating effects may occur in the recycling cavity, when it is not in resonance, but they are negligible because of the low laser power transmitting into the cavity through the RM.

Table 2: Temperature rise of target suspension wires in 2K IFO

ROGUE MIRROR	TARGET MIRROR	SPOT SIZE, mm	POWER DENSITY, W/m^2	ENERGY DENSITY, J/m^2	TEMP RISE, deg C
MMT2					
	MC1,3	33	1779		64
	SM1	33	1779		64
	SM2	29	2271		73
	MMT1	32	1865		66
	MMT3	32	1865		66
MMT1					
	MMT2	3.0	212207		704
	MC2	3.3	175377		640
	RM	4.1	113614		515
MC2					
	MC1,3	1.8		44210	110
	MMT3	1.8		44210	110
	MMT1	1.8		44210	110
	SM1	1.8		44210	110
BS					
	FMX			0.23	0.00
RM					
	FMY			0.23	0.00
ETM					
	ITM	32		5440	2

3.3 4K IFO Suspension Wire Temperature Rise

The calculations of the temperature rise of various target suspension wires in the 4K IFO are shown in Table 3

- MMT1 is the most destructive rogue mirror. Its errant beams may cause the highest temperature rise of suspension wires at the target locations of MMT2, MC2, and the RM.
- The stored energy in the mode cleaner may be a problematic source of errant energy at the target locations of MC1, MC3, MMT3, MMT1, and SM1.
- MMT2 is a marginally problematic rogue mirror with errant beams at the target locations MC1, MC3, SM1, MMT1, and MMT3.
- The errant stored energy in the arm cavity appears to be relatively benign, because of the low energy density associated with the large spot size at the ITM location.
- The errant stored energy in the recycling cavity is also negligible because of the relatively low finesse and the short storage time. CW heating effects may occur in the recycling cavity, when it is not in resonance, but they are negligible because of the low laser power transmitting the RM.

Table 3: Temperature rise of target suspension wires in 4K IFO

ROGUE MIRROR	TARGET MIRROR	SPOT SIZE, mm	POWER DENSITY, W/m^2	ENERGY DENSITY, J/m^2	TEMP RISE, deg C
MMT2					
	MC1,3	32	1916		67
	SM1	32	1916		67
	MMT3	36	1484		59
	MMT1	34	1701		63
MMT1					
	MMT2	5.3	67811		398
	MC2	5.0	77538		426
	RM	6.2	49572		340
MC2					
	MC1,3	1.6		54045	134
	MMT3	1.7		52296	130
	MMT1	1.6		53714	134
	SM1	1.6		54045	134
RM					
	ITM	36		0.18	0.00
ETM					
	ITM	36		4298	2

4 Conclusions

In light of the demonstrated damage to the MMT2 suspension wire by an errant laser beam, it is concluded that the suspension wires and OSEM signal cables on MMT2, MC2, and RM are susceptible to damage by errant laser beams from the MMT1 (or SM1/SM2) rogue mirror.

It would also be prudent to place baffles on mirror suspension structures and at locations within the IO beam path to eliminate the line of sight of target suspension wires and OSEM signal cables from all other potential rogue mirrors.

4.1 Potential Rogue Mirrors

Based on the temperature rise estimates of heated suspensions wires by errant beams, it is concluded that in the 2K IFO and in the 4K IFO the MMT1 (or SM1/SM2), MMT2, and MC2 are potential rogue mirrors that might misdirect laser beams and cause damage to the suspension wires and to the OSEM signal cables.

4.2 Recommendations for Protective Baffles

Protective baffles should be mounted on the MC1, MC3, SM1, SM2, MMT1, and MMT3 mirror suspension structures to shield the suspension wires and OSEM cables from the line of sight to the MMT2 mirror and the MC2 mirror.

Baffles should also be placed on the HAM1/HAM 7 optical tables in order to shield all OSEM cables from the line of sight of MC2 and MMT2.

Protective baffles should be mounted on the MC2 and MMT2 mirror suspension structures to shield the suspension wires and OSEM cables from the line of sight to the MMT1 (or SM1/SM2) mirror.

A baffle should be placed on the AR side of the RM to shield the suspension wires of the RM from the line of sight of the MMT1 (or SM1/SM2) rogue mirror.