LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Single Test Cavity Design and use of the Xarm for LASTI

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1 Introduction

1.1 Introduction to Problem and History

Proposed LASTI experiment utilized a two cavity layout (see for example G010269-00-R) to provide common mode rejection of the frequency noise on the light transmitted through the mode cleaner. It was realized in early 2003 that the total mass of the two quad suspension systems on the BSC seismic isolation system may exceed the mass limit of the BSC seismic isolation system. A number of solutions to this problem were proposed:

1. Alter the design of the LASTI BSC seismic isolation to accommodate the full mass of LASTI. This was generally thought to be quite an involved undertaking and as it did not have any clear benefits to Advanced LIGO beyond getting the LASTI experiment to work, hence it was deemed inappropriate.
2. Drop the second test cavity and evaluate the likely performance of the LASTI system. This option is evaluated in this report.

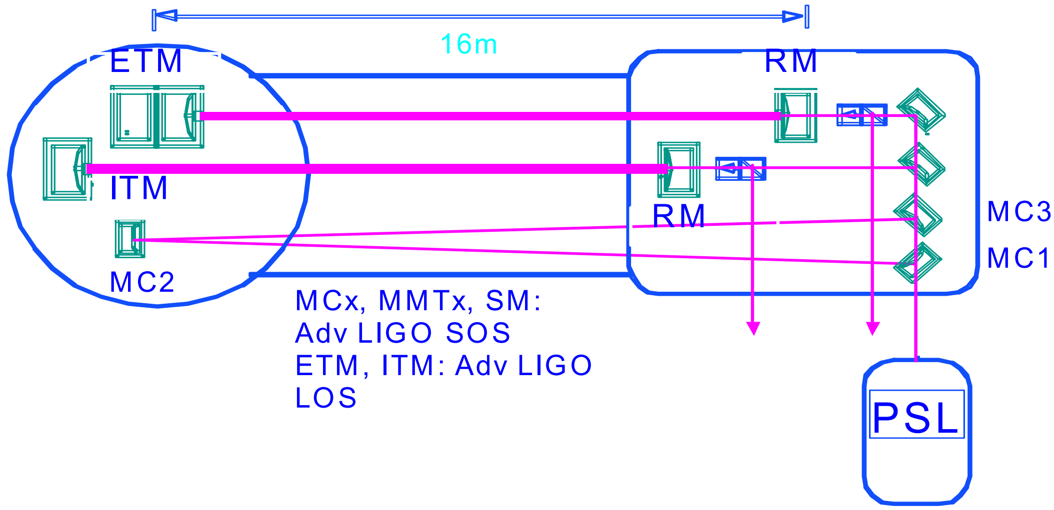

Figure 1-1 Two Test Cavity LASTI

1.2 Relevant Documents and Articles

Gregg Harry, Ken Mason, David Ottaway and Mike Zucker *"Advanced System Test Interferometer (LASTI): Program Status Report",* LSC Meeting August 13 - 16, Hanford WA, LIGO Document G010269-00-R

Calloni E, Barone F, Di Fiore L, Grado A, La Penna P and Milano L, "*Effects of misalignment and beam jitter in Fabry-Perot laser stabilization*" Optics Communications 142 (1997) 50-54

2 Likely limits on the LASTI Mode Cleaner Frequency Noise

With a single test cavity the performance of the mode cleaner becomes critical in determining the absolute noise performance of the system. This is particularly true when the mode cleaner and the test cavity are of the same length. Both the MC and the Test Cavity need to use the full length of LASTI. The modecleaner to achieve maximum frequency noise suppression, the test cavity to maximize the spot sizes on the test cavities and hence limit the effect of thermo-elastic noise, the limiting noise source for sapphire substrates.

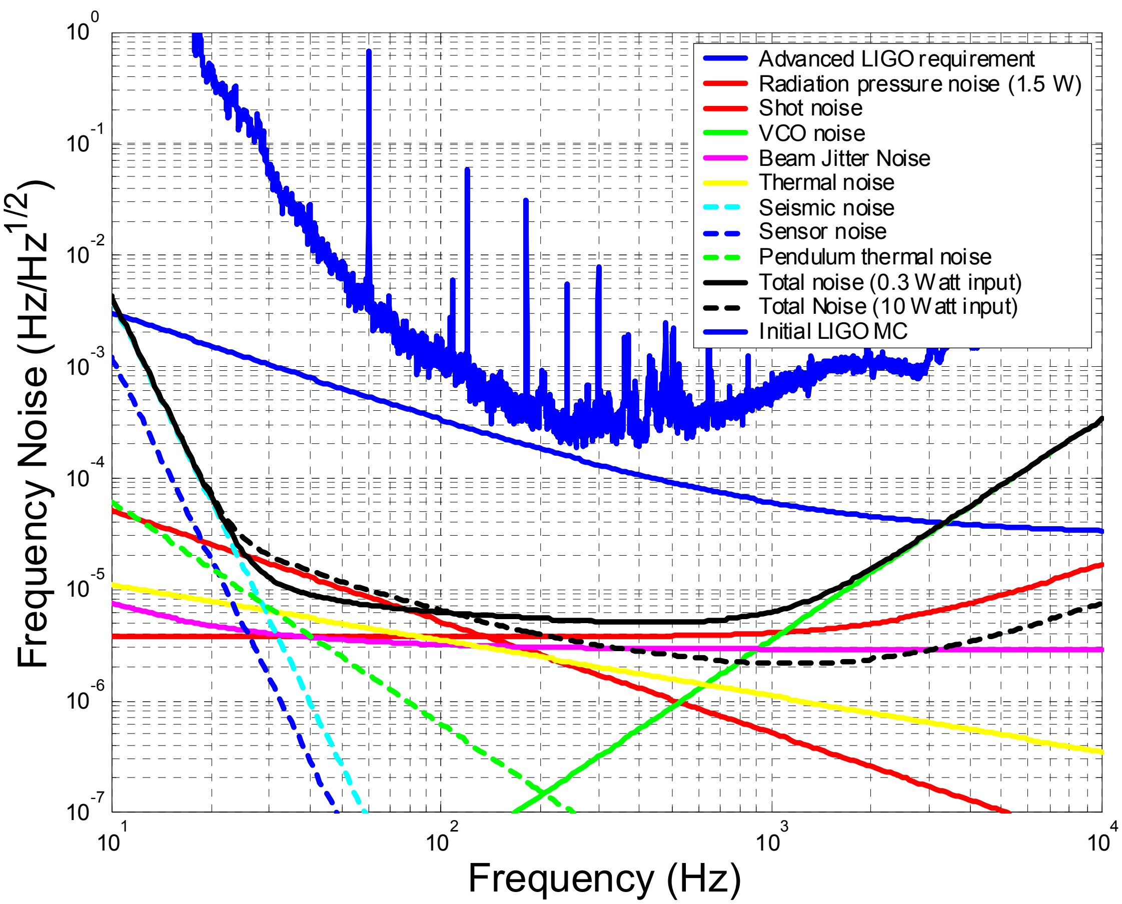

Figure 2-1 Predicted MC Frequency noise properties

Because the mode cleaner mirrors are significantly lighter than the test mass substrates the mode cleaner mirrors will be more significantly adversely affected by radiation pressure noise. For this reason it is anticipated that to obtain the greatest amount of information from the LASTI program the experiment will need to be conducted at several different levels of input power -- low levels (0.3 - 1.5 W) and at full power (180) for the final PSL-IO integration test. In addition to this, it is anticipated that the performance of the mode cleaner at low frequencies will be limited by the high seismic noise in Cambridge, MA. This is due to insufficient loop gain in the proposed seismic system to suppress the seismic noise environment to the sensor noise limits. However, in LASTI resonant gain could be used to cut this seismic noise down and a series of limited frequency band measurements could be made to force the MC performance down to the next noise source at low frequencies. This would validate the overall performance of the instrument down to the level of the MC sensor noise.

One of the limiting noise sources in the MC system is the Voltage Controlled Oscillator (VCO) driver noise. Included in the above plot is the noise level of the VCO driver for LIGO 1. It anticipated that a reduction in its range and improved electronics should reduce this level appreciably (Personal Communication with Rana Adhikari).

The beam jitter noise was calculated using performance data from LIGO1 PSL and utilizing the formulae given by Calloni *et al.* Beam Jitter noise looks like a contributing noise source for the tests at 1.5 Watts input power. However, beam jitter at these frequencies is very hard to measure, hence, this number is derived from a very conservative estimate of the beam jitter at 200 Hz. In all likelihood it could be appreciably below this.

3 Performance of the LASTI Test-mass suspension cavities

The likely noise sources for a LASTI test cavities are shown below for 0.3 and 1.5 Watts of incident power. The limiting noise sources in the 0.3 watt regime are: Seismic noise from the recycling mirror triple, suspension thermal noise from the recycling mirror triple and thermo-elastic noise in the sapphire test mass. Also shown on the plots are the predicted mode cleaner noise sources in for each power level. In the 0.3 Watt incident power case with recycling a mirrors it seems quite likely that the mode cleaner frequency noise will not limit the experiment at all. In the case analyzed here, aggressive thermal and aggressive thermo-elastic are the predicted noise performance when a radius of curvature of 2km is used on the quad mirror. For the conservative case a radii of curvature of 160 m is analyzed. In both cases the recycling mirrors are chosen to be flat.

It is clear from these performance curves that for an improved measure of the quadruple suspension at low frequencies, the recycling mirror will need to be substituted for mode cleaner triple suspension to achieve better suspension thermal noise. Hence if a second test cavity is to be pursued it should consist of BSC Quad suspension on the BSC platform and a mode cleaner triple suspension on the HAM platform.

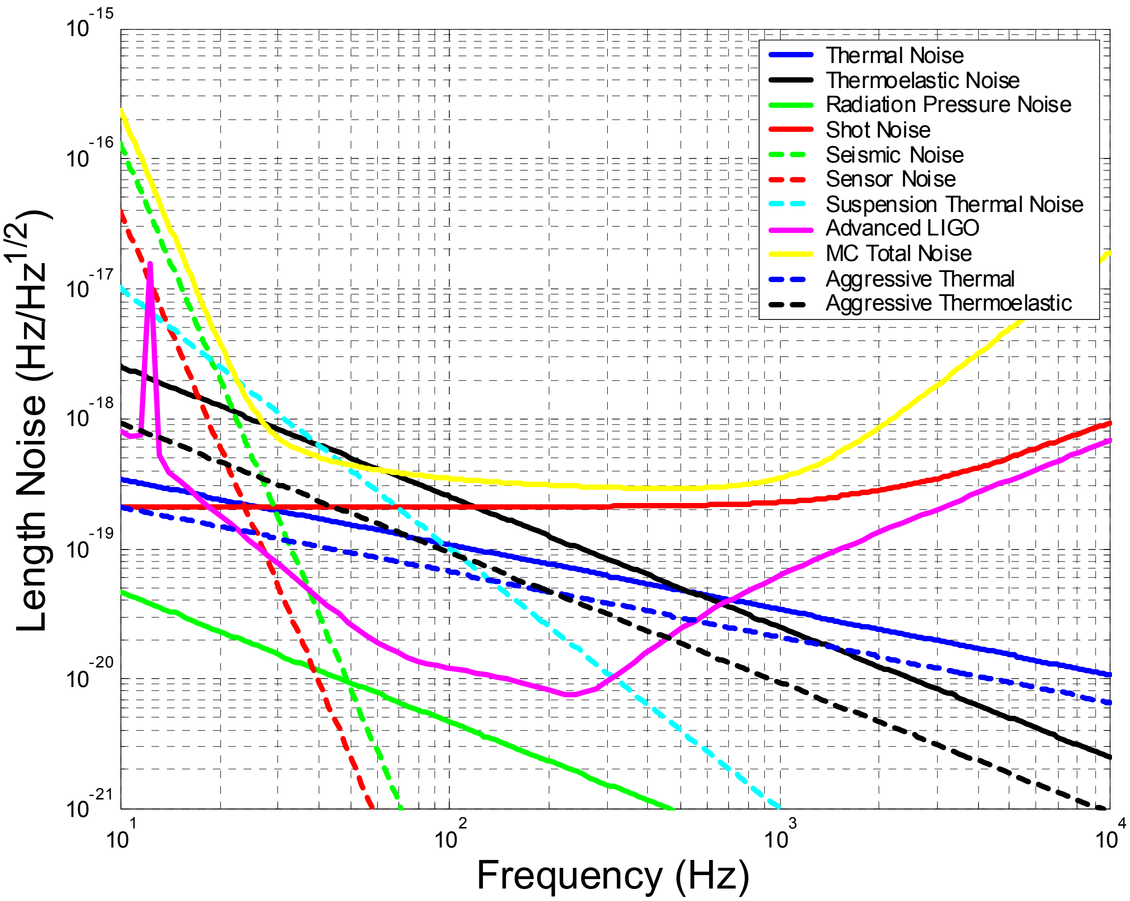

Figure 3-1 Test Cavity Performance for 0.3 Watt incident power experiment, optimum performance in the 10Hz to 100 Hz band

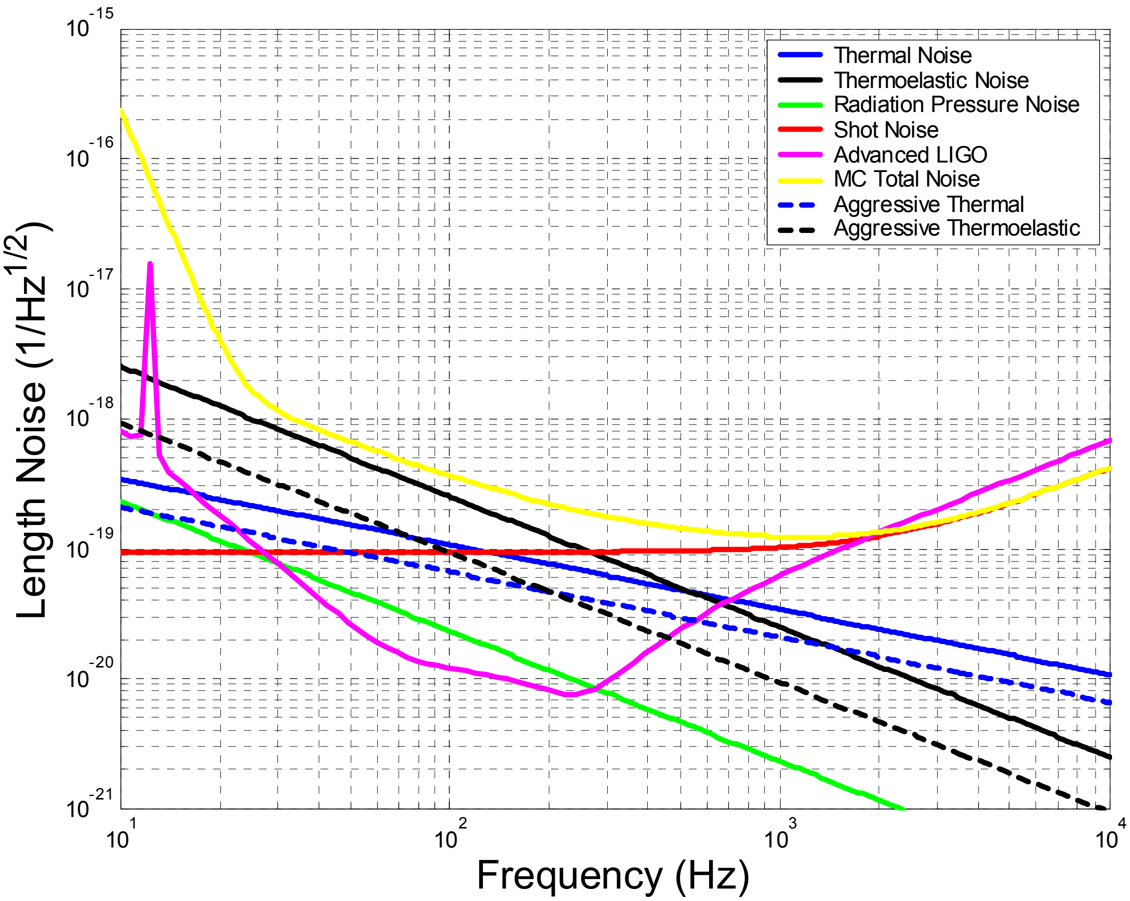

Figure 3-2 1.5 Watt operation of LASTI Test Cavity Performance, optimum noise performance in the 100 Hz to 10 kHz band.

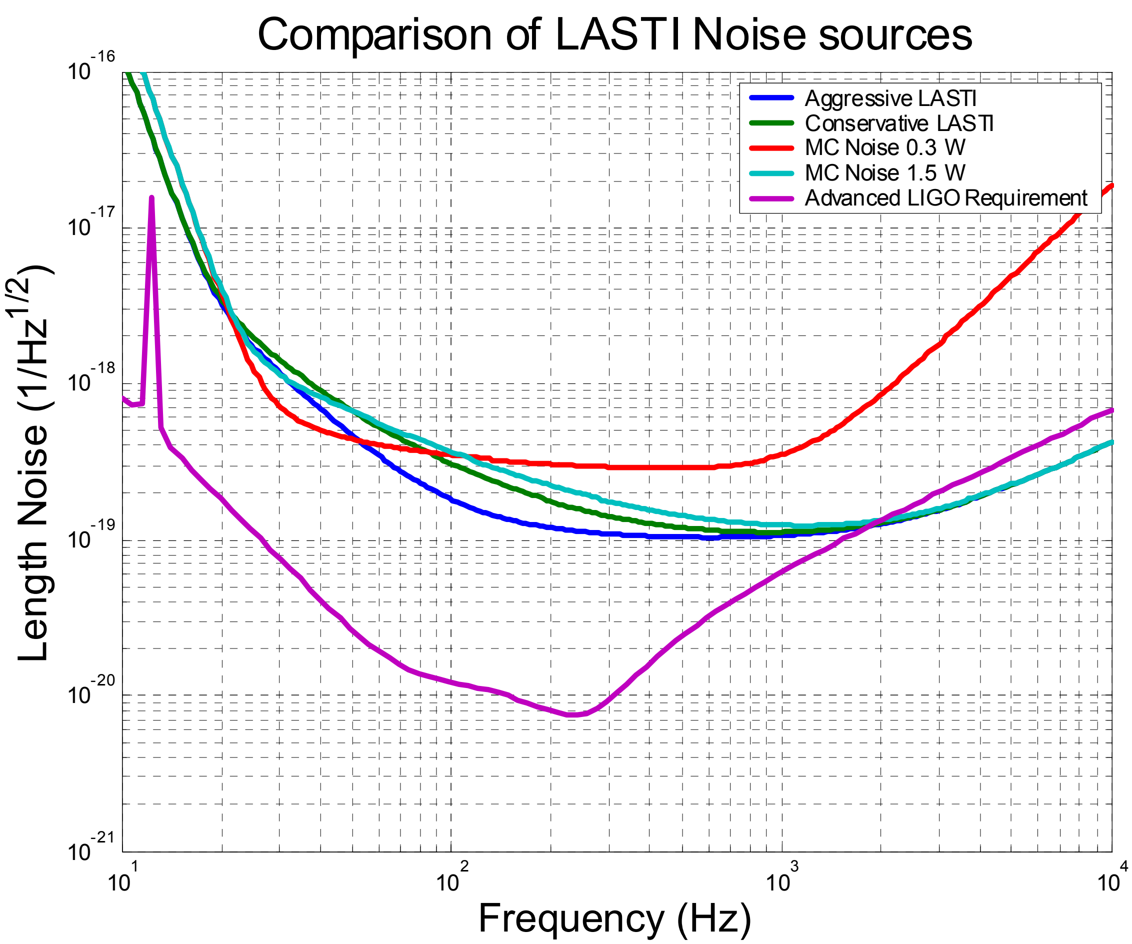

Figure 3-3 Comparison of LASTI Noise Performance

When the combined curves of the low frequency and mid frequency power optimized mode cleaner is considered it is clear that the performance of the mode cleaner is equivalent to that of conservative LASTI. Aggressive LASTI outperforms the MC performance by up to a factor of two in the center region. One of the important areas of consideration for LASTI is the low frequency band. Given this consideration, the performance testing of the Quad test-mass suspension should be performed not with the recycling suspension but with a mode-cleaner suspension. If two test cavities are ultimately employed, it would be best for both to be quad-mode cleaner pairs. (Again, we would want also to test a recycling mirror suspension in any event at an appropriate point in the program.)

4 Weight Issues for the BSC Seismic

It was realized in mid 2003 that the two test cavity approach would exceed the payload weight limit of the BSC Seismic platform. A mass budget for the system is presented below:

Element	Mass
ITM Quad Suspension	422.5 Kg
ETM Quad Suspension	472.5 Kg

MC Suspension + Spacer	81.3 Kg + Spacer
Total	976.3 Kg + Spacer
Total allowable BSC Seismic payload	800 Kg

It seems from these numbers that the mass limit of the two test cavity approach significantly exceeds the allowable BSC seismic system payload. However, the mass estimations above include a 25 % contingency; if the final design of the suspensions comes in at their present mass then there should not be a problem.

5 Fitting One or Two Test Cavities in the Xarm

A layout of the high bay is shown in Figure 5.1.

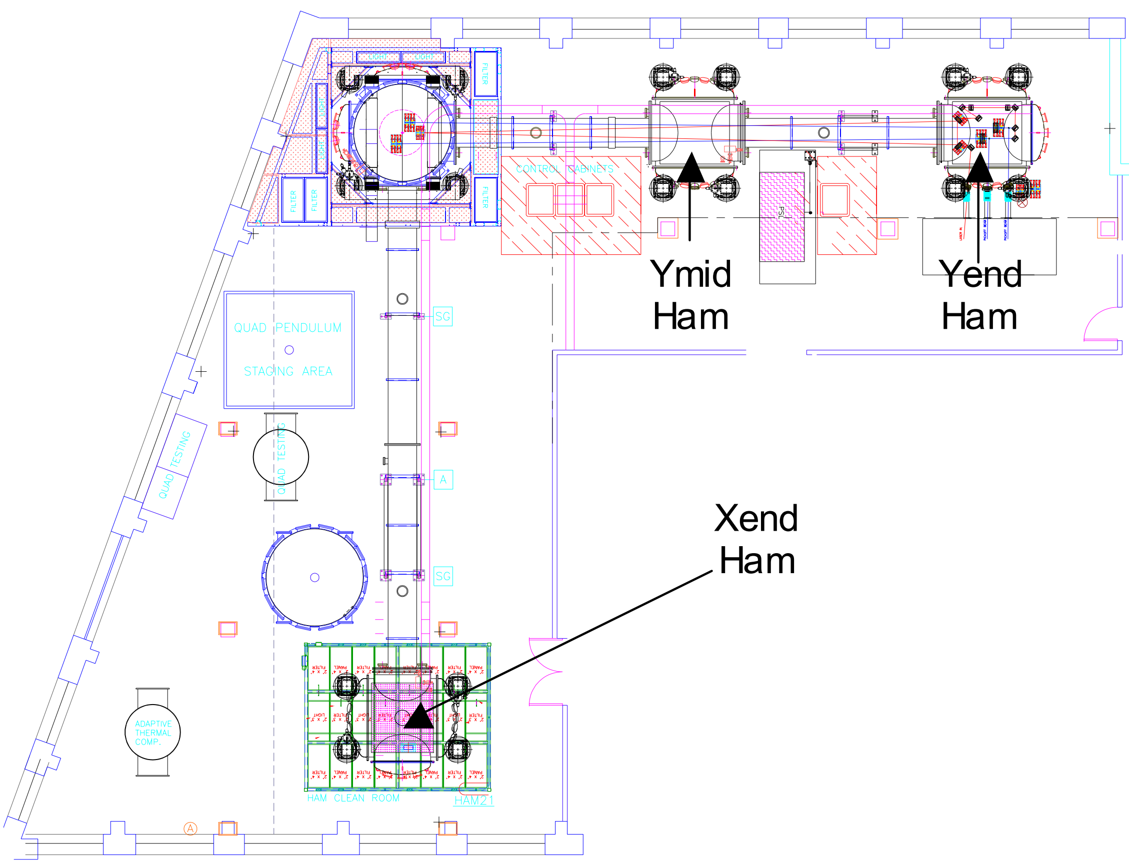

Figure 5-1 LASTI High-bay Layout

The related decision to the case of whether to use one or two test cavities relates to which arm of the LASTI vacuum we choose to use. It is a tight squeeze to fit two test cavities within a reasonable clear aperture in the xarm. Figure 4.1 shows how two quad suspensions can fit in a direction that faces the xarm. From this diagram it is clear that two quad suspensions can fit into the BSC facing the xarm with a 10 cm clear aperture for the shadowed suspension. This makes the positioning of the mode cleaner triple suspension difficult. Given the different beam heights between the mode cleaner and the test cavities and the small mode cleaner beam size it should be possible with some small amount of effort to fit the mode cleaner mirror in such a location that the MC beam passes through the Quad suspension structure.

The Xarm has significant advantages over the Yarm in terms of access to the HAM chamber. This is particularly relevant to the installation of the HAM Seismic isolation system, which is anticipated to weigh approximately 4000 pounds. With the greater access, complete assembly of the HAM Seismic system in a clean room in the high-bay becomes far more feasible.

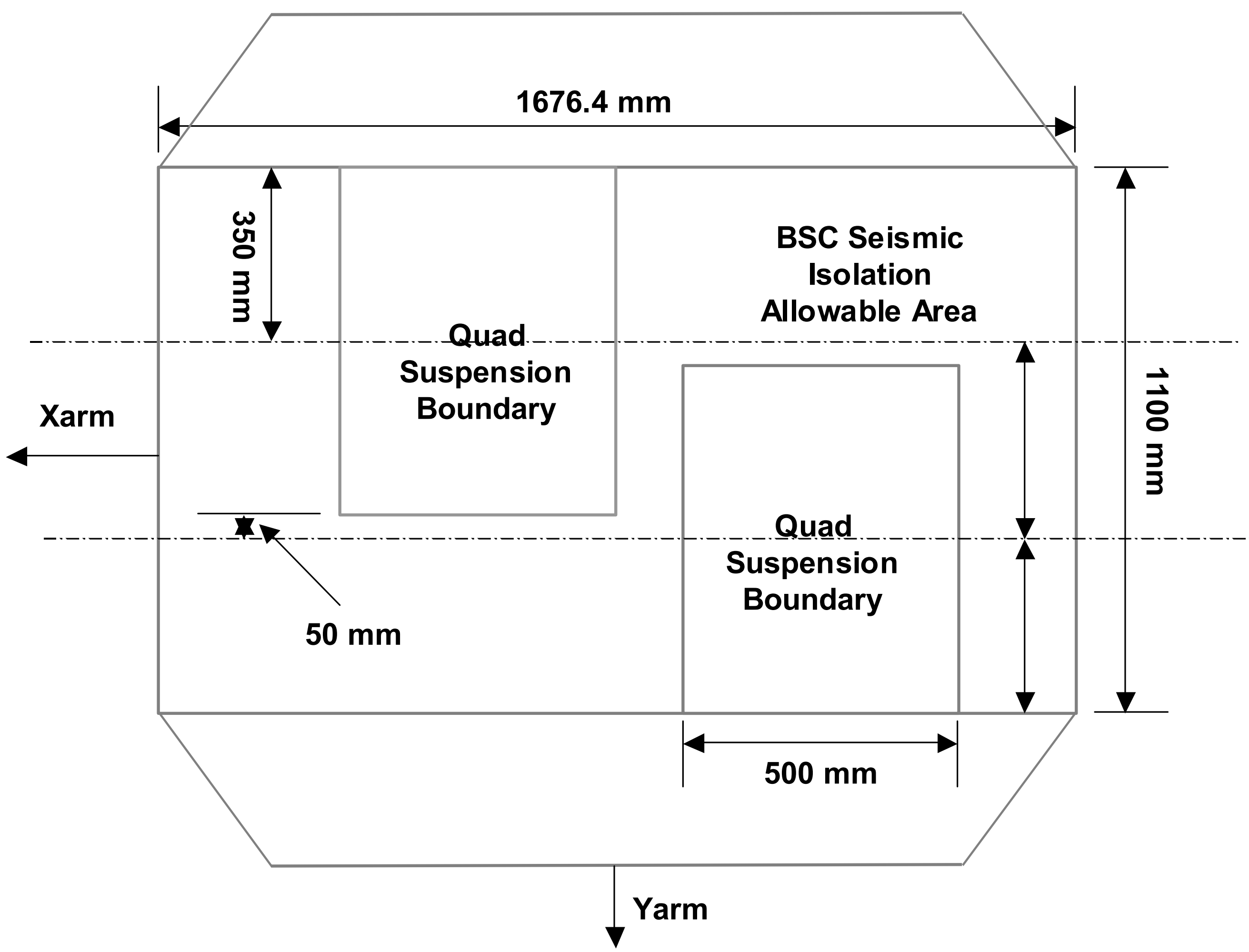

Figure 5-2 How to fit two test cavities in the BSC utilizing the Xarm

The decision on which arm to use is the most pending as we may (depending on the Livingston EPI schedule) be performing a fit check on the production version of the HEPI Ham system. It would be prudent to install this system on the HAM that we plan to later use in the LASTI tests.

6 Conclusions and Recommendations

Assuming that people are happy with the noise model for the mode cleaner it seems likely that significant progress towards testing Advanced LIGO Suspension and Seismic Isolation could be achieved using only one test cavity. The two-test cavity LASTI will possibly significantly exceed the BSC seismic mass limit. The reduction in complexity of the LASTI program that comes with the adoption of a single cavity increases the robustness of the schedule significantly. For accessibility reasons it seems prudent to switch to the Xarm of LASTI. It seems likely that this arm could accommodate a double test cavity if needed. For the aforementioned reasons I recommend that the following changes are made to the LASTI baseline plan:

1. The baseline plan will adopt a single test cavity instead of the planned two test cavity approach. If circumstances are found to require and funding allows, a second test cavity could be reinstated at a later time. If the budget will allow we should carry the second cavity as the LASTI contingency plan. If this contingency is adopted the test cavity should consist of a MC triple and a BSC Quad.
2. The baseline plan will change from using the Yarm to the Xarm to allow far greater access to the HAM chamber. Reversing this decision later on is possible, with a big schedule hit. If it is found later on that the MC performance does not meet the presented expectations and the resources are available to implement a second arm cavity it is possible to fit two cavities in the Xarm with careful re-positioning of the modecleaner

The anticipated effect on sub-systems is :

SUS: The baseline for LASTI prototyping would change from:

one ITM

one ETM

two RM

three MC, one with height adaptor for the BSC

to:

one quad, perhaps re-configurable, which tests aspects of the ITM (thermal compensation) and ETM (reaction mass actuation) as needed, one RM, to be tested before or after the TM-RM cavity is exploited

four MC, one with height adaptor for the BSC

SEI: no impact, unless two cavity design exceeds mass limit then becomes more necessary

PSL/IO: nominally no impact; all high-sensitivity testing performed with present LASTI 10W laser, with the 180W laser and high-power IO components tested in a later phase

Note that the net financial impact on the US program is negligible (one fewer RM prototype and one more MC prototype is needed; the electronics can be shared, as only one will be used at a given time). The UK program would not need to fabricate two quad noise prototypes, but instead we need to test to our satisfaction aspects of both the ITM and ETM on a single somewhat re-configurable quad suspension.

COC: Already have sapphire substrates for LASTI. Will reduce the number of optics that need to be coated and polished.

Appendix 1. List of Parameters used to model MC noise

Cavity Parameters

Length	16
Input mirror reflectivity	0.998
Input mirror transmission	0.002
Output mirror reflectivity	0.998
Output mirror transmission	0.002
Finesse	2026
Modulation depth	0.1
Modulation frequency	25 MHz
Mode matching	0.97
Cavity visibility	1.0
PD quantum efficiency	90 %
MC1 mirror ROC	Flat
MC3 mirror ROC	Flat
MC2 mirror ROC	26.9 m
Cavity spot size	2.7e-3 m

Mirror Suspension Parameters

Number of masses	3
Seismic attenuation at seismic frequency	1.3e-5
Seismic frequency	10 Hz
Sensor attenuation at sensor frequency	3.9e-6
Sensor frequency	10 Hz
Suspension thermal noise at thermal frequency	2e-18 m/rtHz
Suspension thermal frequency	10 Hz

Sensor noise at sensor frequency	1e-11 m/rtHz
Seismic noise at table top at seismic frequency	1e-11 m/rtHz
Substrate mass	3 kg

Mirror Optical Properties

Coating Parallel Phi	5.0e-5
Coating Perpendicular Phi	5.0e-5
Coating Young's modulus	1.0e11
Coating Poisson Ratio	0.20
Coating thickness	1e-5 um
Substrate Phi	3e-8

Appendix 2. List of parameters used to model test cavity noise

Cavity Parameters

Length	16
Input mirror reflectivity	0.996
Input mirror transmission	0.004
Output mirror reflectivity	1.0
Output mirror transmission	0.0
Finesse	2026
Modulation depth	0.1
Modulation frequency	9.8438 MHz
Mode matching	0.97
Cavity visibility	1.0
PD quantum efficiency	90 %
Input mirror ROC	Flat
Output mirror ROC	40 m (Conservative)
Output mirror ROC	2 km (Aggressive)
Cavity spot size	2.5 mm (Conservative)
Cavity spot size	7.5 mm (Aggressive)

Input Mirror Suspension Parameters (Recycling mirror)

Number of masses	3
Seismic attenuation at seismic frequency	1.3e-5
Seismic frequency	10 Hz
Sensor attenuation at sensor frequency	3.9e-6

Sensor frequency	10 Hz
Suspension thermal noise at thermal frequency	2e-16 m/rtHz
Suspension thermal frequency	10 Hz
Sensor noise at sensor frequency	1e-11 m/rtHz
Seismic noise at table top at seismic frequency	1e-11 m/rtHz
Substrate mass	15 kg

Output Mirror Suspension Parameters (Test mass mirror)

Number of masses	4
Seismic attenuation at seismic frequency	2.8e-7
Seismic frequency	10 Hz
Sensor attenuation at sensor frequency	1.8e-7
Sensor frequency	10 Hz
Suspension thermal noise at thermal frequency	1e-19 m/rtHz
Suspension thermal frequency	10 Hz
Sensor noise at sensor frequency	1e-11 m/rtHz
Seismic noise at table top at seismic frequency	1e-11 m/rtHz
Substrate mass	40 kg

Input Mirror Optical Properties

Coating Parallel Phi	5.0e-5
Coating Perpendicular Phi	5.0e-5
Coating Young's modulus	1.0e11
Coating Poisson Ratio	0.20
Coating thickness	1e-5 um
Substrate Phi	1e-7

Output Mirror Optical Properties

Coating Parallel Phi	5.0e-5
Coating Perpendicular Phi	5.0e-5
Coating Young's modulus	1.0e11
Coating Poisson Ratio	0.20
Coating thickness	1e-5 um
Substrate Phi	1e-8