LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Enhanced LIGO

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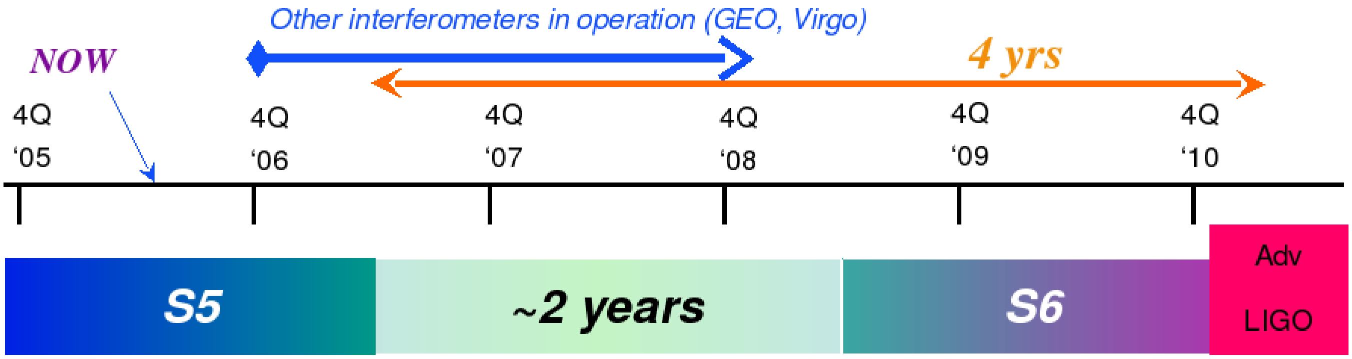


Figure 1: Rough timeline of Enhancements

1 Overview

This document presents the baseline plan for enhancing aspects of the LIGO detectors in the time period between the end of the fifth Science Run (S5) and the start of Advanced LIGO.

All of the main hardware improvements are direct implementations of Advanced LIGO technologies and techniques. This strategy allows us to test full-scale prototypes of the Advanced LIGO system in a low-noise environment.

The principal change is an increase in the laser power aimed at increasing the sensitivity above 100 Hz by a factor of ~2.5. To take advantage of the increased laser power, the dark port sensing system will be moved in vacuum onto a seismically isolated platform and a filter cavity will be installed in the beam path to clean up the light.

The plan described here implements these improvements on only the two 4km interferometers. A staged installation schedule will allow the commissioning team at Livingston to discover problems in time to inform the work being done at Hanford. Post-S5 tasks for the Hanford 2 km instrument are still being discussed and are outside the scope of this document.

Astrophysical motivations for this sensitivity improvement are detailed in T050252[1].

2 Timeline and Current Status

2.1 Present Status of the Noise

The S5 Science Run started off with the interferometers at the sensitivity goal set for the start of the run. Further characterization of the instruments throughout the run led to further improvement of ~30% in the sensitivity to neutron star inspirals. The following plot shows the equivalent strain noise of all 3 interferometers and also the sensitivity goal from

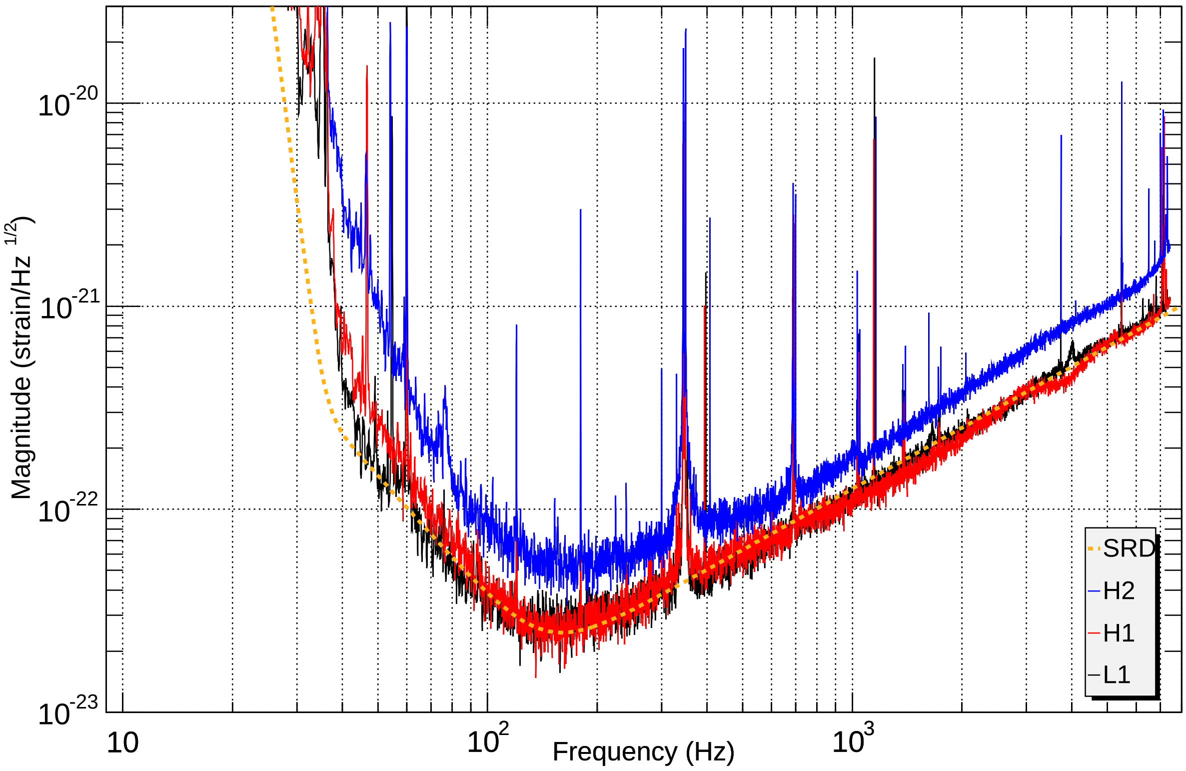


Figure 2: Best strain noise curves circa June, 2006[8]

the Science Requirements Document (SRD)[2].

The excess noise below 100 Hz is not well understood. It is further discussed in the section on upconversion (A.3).

3 Detector Enhancements

In this section, the major detector enhancements are described.

3.1 Increased Laser Power

To increase the laser power a new Master Oscillator / Power Amplifier (MOPA) will be installed. These new units will be provided by our German Advanced LIGO partner, the Albert Einstein Institute, and manufactured by the Laser Zentrum Hanover (LZH). The plan is that AEI/LZH will make an early delivery of the front-end of the Advanced LIGO high-power lasers. These MOPA front-ends provide 30-35 W in the TEM00 mode, around 3x more than our existing MOPA.

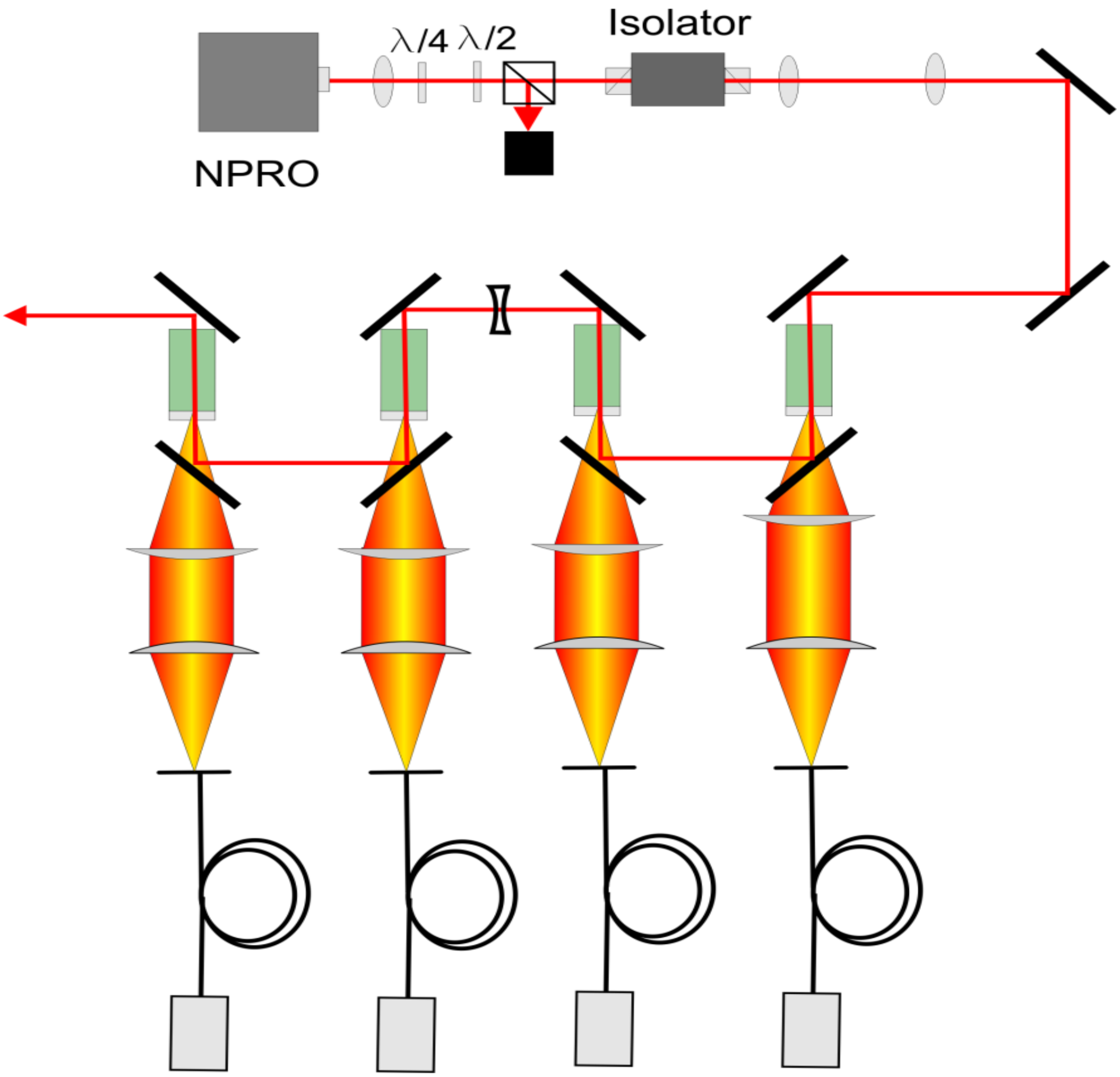


Figure 3: Diagram of the 30 W MOPA system

The LZH MOPA consists of an Innolight 2 W NPRO master oscillator, amplified by four end-pumped rods of Nd:YVO_4[3]. This is a relatively recent alternative front-end design for the AdLIGO high-power laser, the original design being an injection-locked, 12 W oscillator. The MOPA design is preferred due its simplicity and higher-power, which helps with the injection locking of the high-power stage. By installing and operating these MOPAs in the enhancement phase, we will gain valuable experience with such a substantial piece of the Advanced LIGO PSL system.

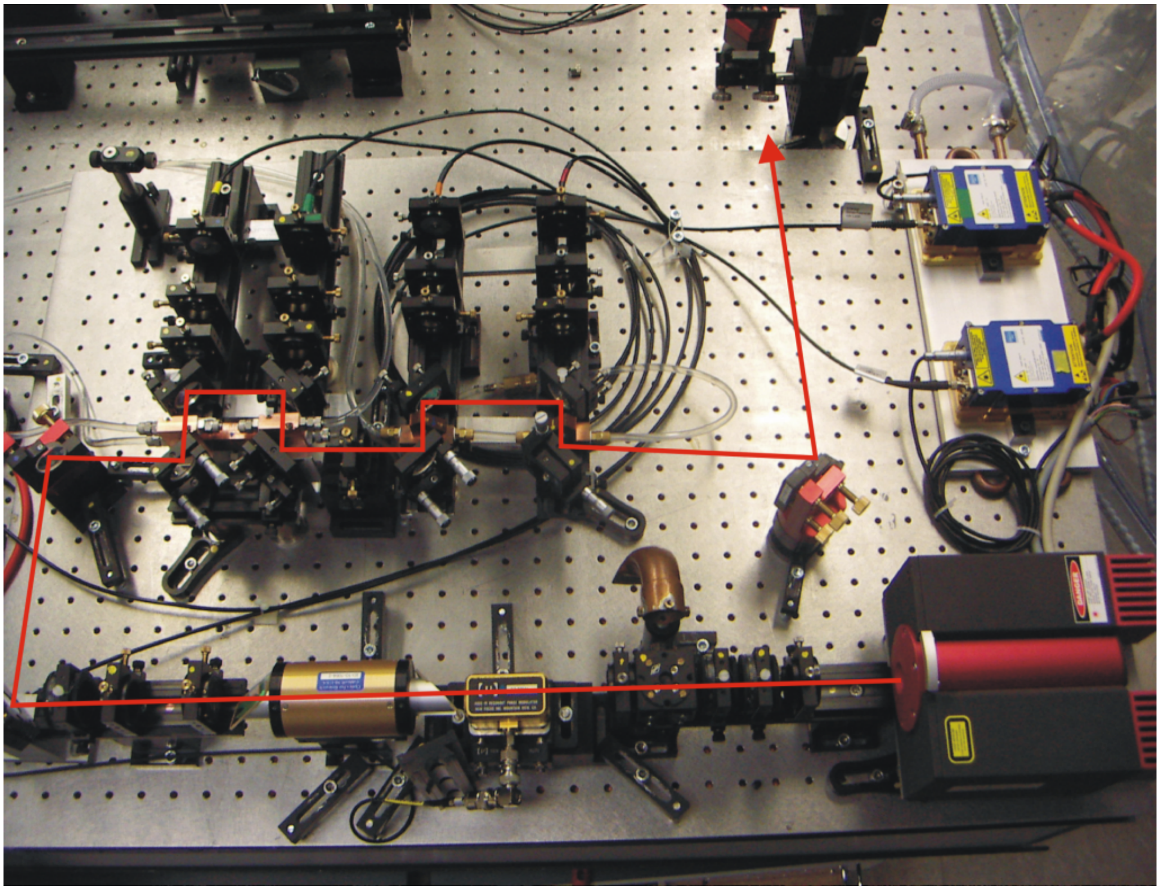


Figure 4: Photo of the prototype laser at LZH

Incorporating these lasers into our interferometers will require some work, but should be fairly straightforward. The pump diodes and diode electronics are to be installed in the mechanical room adjacent to the LVEA, with the diode light output delivered to the amplifier rods through fibers. The mechanical room will have to be outfitted with proper electrical services and space requirements. LIGO will need to supply the electronics and interfaces for the monitoring and control of the laser.

No major changes to the existing laser frequency (FSS) and intensity (ISS) servos will be needed. Frequency actuation of the Innolight NPRO is very similar to that of our existing NPROs; a couple of circuit component values or connectors may need to be changed. The power actuation scheme of the MOPA has not yet been defined, and could either be a current shunt on the amplifier diode(s), or an acousto-optic modulator before the amplifier; either could be incorporated into our ISS.

Currently LZH is manufacturing an amplifier of the above design for the Virgo project, to be delivered at the end of 2006. Ideally, we would like a first LZH MOPA delivered to LIGO in the first half of 2007, so that it could be tested at Caltech prior to being installed at an observatory. It is not clear yet whether the schedule would allow the testing period at Caltech, as no specific delivery schedules have been offered by LZH.

3.2 Dark Port Sensing

There are three major components to the new dark port sensing scheme:

- DC Readout of the gravitational wave signal (as opposed to RF heterodyning)
- An Output Mode Cleaner (OMC) cavity to remove junk light before detection
- All in-vacuum detection hardware (optical table, photodetectors, auto-alignment)

The DC readout scheme (with OMC) is being prototyped at the Caltech 40m lab this year (2006). This includes all of the same hardware which will be needed at the observatories and all of the design work so far has been done keeping in mind the requirements for the post-S5 enhancement as well as Advanced LIGO.

3.2.1 DC Readout

DC Readout is the baseline scheme for Advanced LIGO[4]. The current interferometers use an RF readout scheme[9]; a local oscillator field, shifted by ∼30 MHz from the carrier, is present at the dark port. The resulting beat signal is synchronously demodulated to recover the gravitational wave signal. This RF heterodyne scheme has historically been used to escape some of the technical noise sources associated with audio band measurements (e.g. laser noises).

In the DC scheme, the arm cavities are shifted slightly off resonance, which shifts the signal at the dark port slightly from the dark fringe. The power at the dark port becomes a linear readout of the differential arm length.

There are a number of potential technical advantages to using this scheme. The coupling from several technical noise sources is reduced: laser frequency noise, power recycling cavity length noise, RF oscillator noise, etc. See Appendix C for the detailed technical analysis.

However, DC readout has never been demonstrated on a complex, suspended interferometer. The CIT 40m lab is taking this on currently[30]. The purpose of the 40m lab's DC readout experiment is to gain more knowledge about problems with this scheme, however, the noise in that interferometer is not low enough to qualify the noise performance of the DC readout / OMC scheme. The first demonstration of that will be at the sites.

3.2.2 Output Mode Cleaner

In both the RF and DC readout schemes, it is advantageous to have an Output Mode Cleaner (OMC). The OMC is a non-degenerate Fabry-Perot ring cavity which is designed to transmit mainly the TEM_{00} mode of the beam at the dark port. This reduces shot noise by reducing the amount of 'junk' light on the photodetector.

In the DC readout scheme, this filter cavity strips off all of the RF sidebands as well as the higher order transverse modes of the carrier and sidebands. In addition to reducing the shot noise level the coupling of various technical noises are also reduced.

The baseline is the same as for Advanced LIGO: a short (∼20 cm), monolithic, ring cavity with a Finesse of ∼300. As part of the DC readout prototyping effort at the CIT 40m lab, a design study will be undertaken to decide on parameters for the Enhanced LIGO OMC.

A short, 3-mirror OMC is in the baseline design for both the GEO600[10] and Virgo[11] detectors. The GEO600 OMC was not implemented in time for the S5 run and at the time of this writing, the Virgo noise floor[13] is not low enough to qualify their OMC's noise performance.

An OMC was installed on the Hanford 4K interferometer in 2004[7]. Although it did, in fact, clean the mode, too much excess noise was introduced in the GW band for this to remain in the sensing chain. It is believed that the excess noise came from higher-order transverse modes passing through the OMC after reflecting off the jittering mirror mounts on the table. The DC readout OMC should avoid these problems by being in vacuum and having a higher finesse and therefore better rejection of higher order modes.

3.2.3 In-vacuum Hardware

The Initial LIGO experience has taught us that placing any of the interferometer's sensors outside of the vacuum introduces a large susceptibility to environmental noise (acoustics, seismic) as well as dust, etc. The chief motivation in moving towards an in-vacuum, isolated platform is to reduce the coupling of these noise sources. This requires the development of a few new techniques: in-vac low noise, DC photodetection. etc.

HAM5 and HAM6 are both empty in the current interferometer layout. After S5, the plan is to insert a vacuum flange with a Brewster angle window between HAM6 and the beamtube connecting HAM5 and HAM6.

A major part of the in-vacuum hardware will be the introduction of an Advanced LIGO HAM isolation table in HAM6. Although this is more isolation than is required for the kind of beam jitter we expect from the initial LIGO interferometer, it is another good opportunity to commission, ahead of time, another Advanced LIGO sub-system.

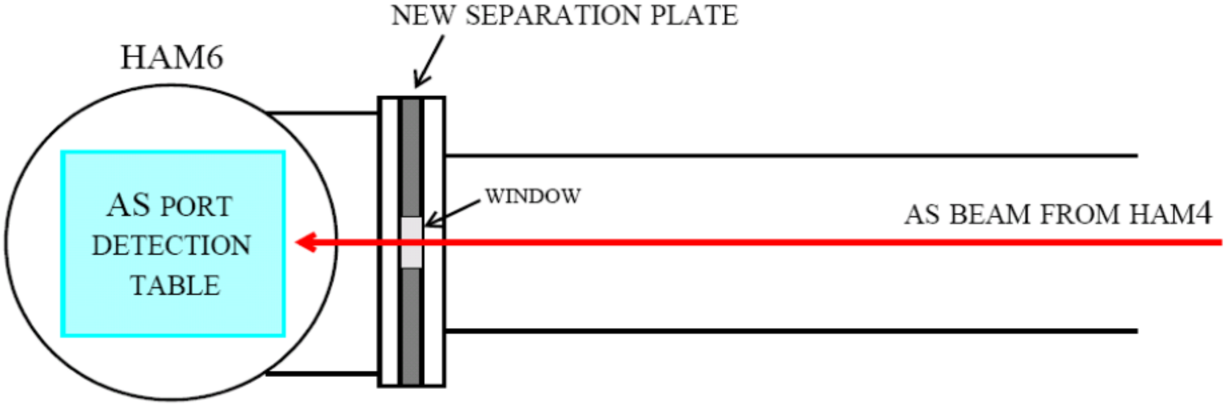


Figure 5: Schematic location of new detection table

The HAM isolation mechanics and control systems will be prototyped at LASTI and also at LLO in the Staging Building.

3.3 High Power Issues

A 3x increase in the laser power requires upgrades in a few of the auxiliary optics systems. Most notably in the Input Optics (Electro-optic modulators and Faraday Isolator) and in the Thermal Compensation System (TCS) for the test masses. The Preliminary Design[5] for the Advanced LIGO Modulators and Isolators describes in detail the proposed upgrades to be made to the initial LIGO hardware. A preliminary design review of these components was held in April 2006; the R&D is well advanced and the University of Florida group is prepared to supply new modulators and isolators for the enhancement phase.

3.3.1 Electro-Optic Modulators

The current $LiNbO_3$ modulators have an operational power limit of around 10 W; (anisotropic) thermal lensing makes them unsuitable for much higher power. The new EOM design uses a crystal of RTP, which has a much lower absorption coefficient at 1064 nm than $LiNbO_3$. The crystals are procured from the crystal grower and packaged into modulators by the Univ. of Florida group. All three post-PMC modulators will be replaced; the number of new RTP modulators is yet to be determined, as more than one modulation frequency may be applied to a new modulator.

3.3.2 Faraday Isolator

The initial LIGO Faraday Isolators exhibit some thermal deflection, leading to a significant beam drift between the interferometer's locked and unlocked states. This has been mitigated somewhat by with the use of active beam steering on the beam rejected by the isolator, though the full range of this system is needed at the present power level, and would not work at much higher power. In addition, thermal lensing may start to significantly alter the beam mode at $3 - 4\times$ higher power. The Advanced LIGO Faraday design solves these problems at the source through the use of: selection of low-absorption TGG; a double-TGG plus quartz rotator design for depolarization compensation; a negative dn/dT element for thermal lens compensation; better polarizers for improved optical efficiency and smaller beam drift. The elements of the new rotator have been successfully tested at high power. The remaining tasks are selection of the polarizer configuration, and refining and completing the opto-mechanical design.

3.3.3 Thermal Lensing

The Initial LIGO optics were designed with a Radius of Curvature (ROC) requiring thermal lensing of the ITM high reflector and substrate to achieve optimal coupling between the arm cavity modes and the power recycling cavity modes. The thermal lensing depends on the absorption of the substrate and the optic surfaces and is particularly sensitive to the poorly controlled surface absorption and the input YAG laser power. Initial LIGO employs a Thermal Compensation System (TCS)[12] to project central and annular heating patterns with 10 μm CO_2 laser radiation onto the ITMs to correct the ITM ROCs and optimize the thermal lensing.

The Enhanced LIGO DC readout scheme relaxes the arm cavity to power recycling cavity mode-matching requirements. However, the increase from 8 W to 30 W of input laser power and the associated increase in central thermal lensing requires an upgrade in the TCS system to correct the ROC using annular heating. Table 1 estimates the Enhanced LIGO TCS requirements based on measurements at H1 made in the summer of 2006.

Optic	YAG-induced central lens	Annulus correction	Required CO_2 power	Thermo-elastic noise
ITMX	225 mW	2.5 W	5.8 W	3.8×10^{-19} m/$\sqrt{Hz}$
ITMY	356 mW	3.9 W	9.1 W	5.9×10^{-19} m/$\sqrt{Hz}$

Table 1: The calculated TCS requirements for 30 W of input YAG power. The central lens is the calculated amount of CO_2 power required to create the same thermal lens as the 30 W YAG light. The annulus power required to correct the central lens assumes an 11:1 efficiency for generating ROC at the optic center. The required CO_2 power is based on the current TCS optical bench and the thermoelastic-elastic noise is calculated based on an early description of the TCS system[31].

The current TCS system uses an 8 W CO_2 laser which is too small to compensate the increased YAG-induced thermal lensing of Enhanced LIGO. Although TCS has been implemented in the past with a 20 W CO_2 laser, excessive intensity noise of the CO_2 beam caused unacceptable thermoelastic-elastic noise in the test masses. The high annulus TCS power needed for Enhanced LIGO will require an upgrade of the CO_2 laser to a 20 W model with intensity stabilization while reusing the remainder of the TCS optical system.

3.3.4 Radiation Pressure

At high circulating powers, Fabry-Perot cavities become unstable to small angular misalignments[6]. Preliminary estimates of the effect on the initial LIGO cavities indicate that a 3x increase in the laser power will move the unstable mode frequency close to the edge of the range of the control systems.

It may be that we can successfully operate the interferometer at such high power with instabilities, but more detailed modeling work is needed to see if that is so or if modifications to the control system are necessary. Since it is certainly also an issue for Advanced LIGO, this is a good opportunity to prototype control software which would have an adaptive 'anti-optical spring' to compensate this effect.

3.4 Misc. Enhancements

Beyond the main enhancements described above there are a list of other enhancements which give modest sensitivity improvements for some moderate amount of effort. These are not necessarily all tasks that will help towards understanding Advanced LIGO.

3.4.1 Cleaning the Mode Cleaner

We know from previous budgets of the input optics transmission[23] that the transmissivity of the suspended, input Mode Cleaner is as low as 70-74% (after correcting for imperfect mode-matching). From knowledge of the optics' microroughness and specified scatter loss [20] we expect to get a transmission of 95% or more.

The recent positive experience[16] with drag wiping the H1 ITMY may indicate that we can reduce the losses and thereby increase the amount of power delivered to the interferometer. In principle, we will get a 10% sensitivity improvement for a 20% improvement in IOO efficiency.

3.4.2 New Pre-Mode Cleaner

The Pre Mode Cleaners (PMC) on both IFOs have transmissions of ∼80%. This has been determined to be due to excess scatter loss on the mirrors. The existing PMCs have a moderately high finesse (∼230) to passively filter the amplitude noise on the light at the main modulation frequency.

Going to DC readout will greatly relax this requirement and therefore also the requirement on the PMC finesse. New PMCs with much lower loss and higher transmission have been demonstrated in the LHO optics lab[21]. Using these more careful manufacturing techniques and coating the mirrors for lower finesse we expect to get the transmission back up to 95% or higher, limited only by mode-matching.

To set a new requirement on the PMC finesse we need to measure the RF noise on the LZH lasers; the auxiliary length DOFs still require moderately low RF noise. We have submitted this measurement into the LZH measurement queue and expect to have this result before the end of the year, leaving ample time for a new coating run of PMC mirrors.

3.4.3 Earthquake Stops

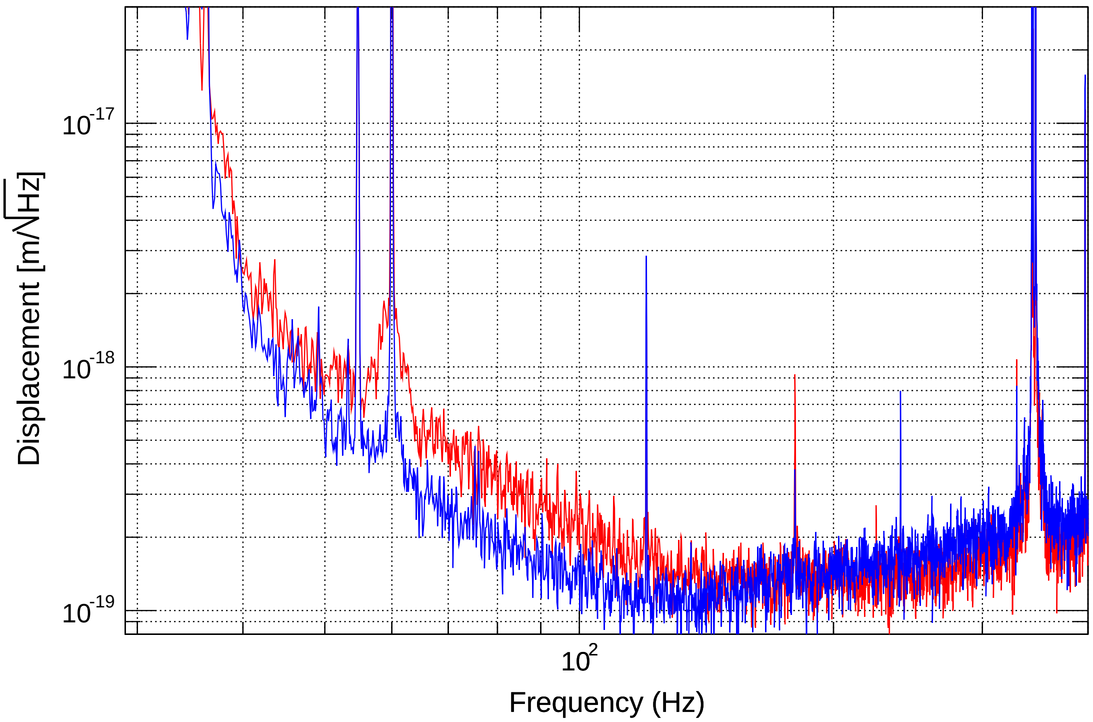


Figure 6: L1 displacement noise before (RED) and after (BLUE) the charging incident.

An exceptional seismic event in Livingston caused the ITMY mirror to repeatedly hit its Flourel earthquake stops. As has happened on other masses on occasion, this resulted in a buildup of excess static charge on the Flourel tips and on the fused silica dielectric coating of the mirror. The electro-static charge was large enough to require a vacuum incursion.

The mirror was freed from contact with its stops and the stops were backed off to restore the nominal 0.5 mm gap. The resulting noise curve (see Figure 6) was 30-50% lower in the 50-130 Hz band. Although there is no definitive theory of this source of excess noise we believe that it is due to excess dissipation either from charge relocations[22] or from the stronger coupling between the mirror pendulum mode and the stops.

Electro-static charge on the optics has long been a concern, and one must assume that the charge-related force noise seen on L1 may be present on the other test masses as well. We propose to address this issue, by reviving a project to replace the (test-mass) earthquake stops with new versions, outfitted with fused silica tips. Having the optic and stop tip made of the same material should prevent charge buildup between them. A couple of prototypes for a new SOS stop were made a couple of years ago; these combined a tip made from a glass rod, with Viton bumpers for damping. The concept is being adapted for the LOS structure, and will also include a finer resolution mechanism for positioning the stop. Note that the suspension earthquake stop design is also an open issue for the Advanced LIGO suspension, and both efforts can learn from each other.

3.4.4 Suspension Electronics

In the 50-100 Hz band, the noise from the suspensions' coil driver electronics comes in just below the estimate of suspension thermal noise. At the time that this latest version of the electronics was designed[28], the interferometer sensitivity was much worse and it was deemed sufficient to meet the SRD/3 level with the electronics. To reduce this noise source we plan to change some components in the coil driver and to completely replace the bias module circuit with a new design:

- The low pass filtering on the PA85 stage in the coil driver is increased by a factor of 2.
- The R-C-R passive filtering at the output of the coil driver is decreased by a factor of 2, reducing the thermal noise contribution from this stage.
- The beamsplitter DAC noise is reduced with a more aggressive dewhitening filter.
- Angle bias modules replaced with low noise units. These will operate at 300 V (instead of 150 V) and have 15 kΩ resistors (instead of 4-7 kΩ) to reduce the thermal noise.

In order to operate with this reduced range on the bias modules, we will have to align the test masses to within 10 μrad of the cavity axis using the adjustable permanent magnets which are bolted onto the backside of the OSEM bobbin. We currently need $\sim$30 μrad[24] of tilt control from the bias electronics but this is largely due to yaw (which can be corrected by mechanical yawing of the external support structure) or pitch from electrostatic charging events which we hope to avoid in the future with the glass earthquake stops.

4 Schedule

The following pages contain the conceptual schedule for the case of the staggered installation.

Livingston begins its vent in the fall of 2007. The time budgeted for the in-vacuum work and the pump down are based upon the historical performance of the experienced installation teams at both sites. In the weeks budgeted for the pump down time we have scheduled a set of tasks which do no require the interferometer. The in-vacuum work in the ends and the following pump down take much less time than the larger volume of the LVEA.

All of the major installation tasks in Livingston involve people from both sites in order to take this time to get everyone educated on the proper installation procedures and to minimize mistakes during Hanford's installation period.

During this time the 2 LHO interferometers will continue to run with Virgo. Depending upon the agreed upon start and end dates of that coincidence run, we would have LHO begin its installation phase ∼2-3 months after LLO. The advantage of this approach is that the lessons learned from the Livingston effort can be applied to shorten the installation and commissioning time at LHO.

The success of the noise reduction phases following the installation is contingent on a great deal of travel to support commissioning from scientists and students at the campuses and also between the observatories as the need arises.

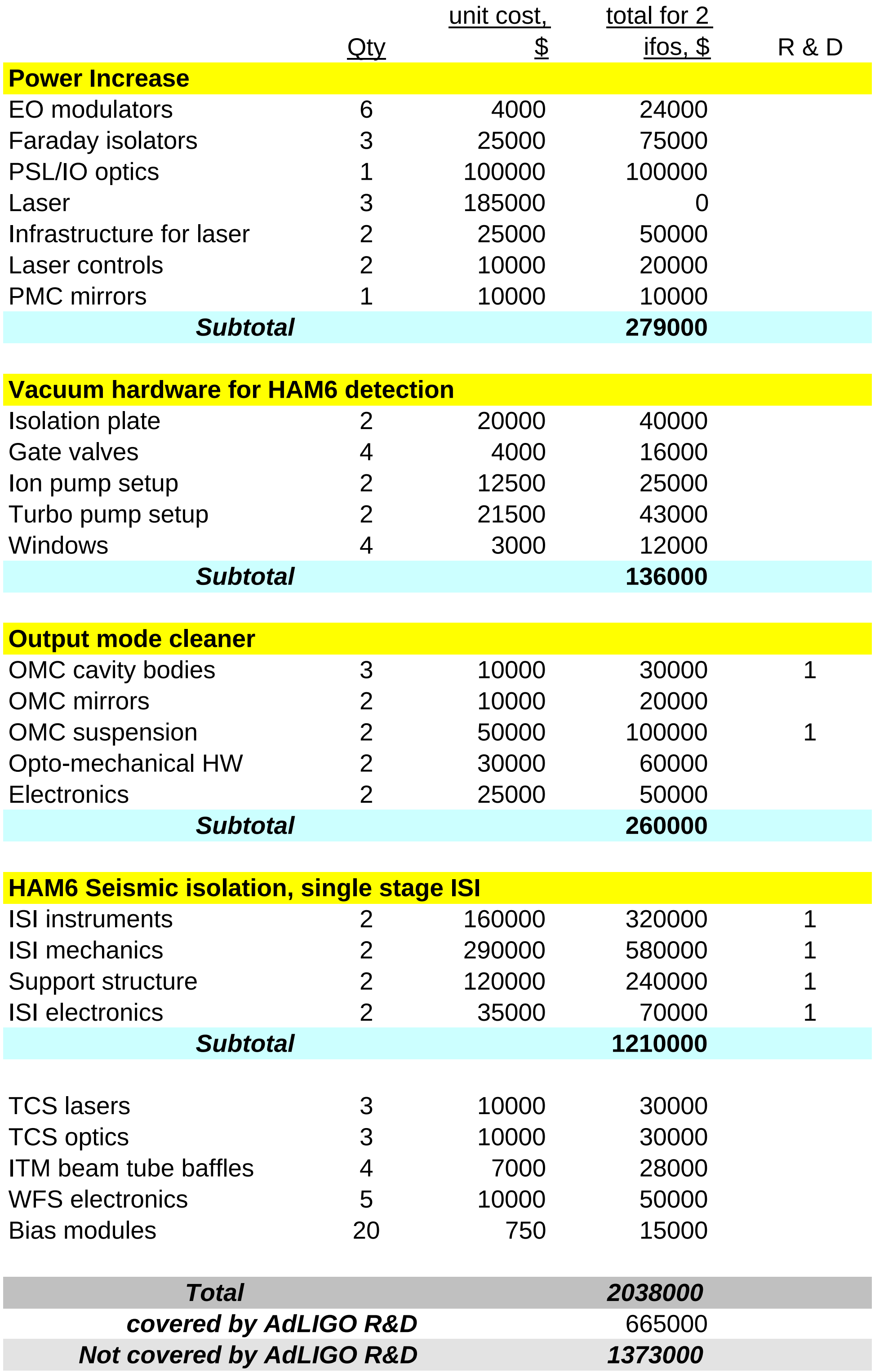
4.1 Livingston

```
 Vent part 1  -   3 weeks
-----------------------------------------
 1) HAM6 flange / window                (Wooley, Overmier, Giaime)
 2) HAM4 telescope re-alignments        (Smith, Bland, Hoak)
 3) Faraday Isolator                    (UF, Rakhmanov, Franzen, Amin)
 4) ITM Re-alignments w/ PAMs           (Traylor, Hanson)
 5) ITM Arm Cavity Baffles              (Traylor, Sellers)
 6) Drag Wipe the MC                    (UF, Bland)
 7) ISS Pickoff move (part of FI install)
 8) Laser electronics installation (King, Fyffe, Wooley)  (through pump down)

 Pump Down    -   6 weeks
---------------------------------------------
 1) HAM installation                    (Overmier, Radkins, Gray, O'Reilly, Giaime)
 2) OMC + HAM6 Optics                   (Frolov, Hoak, Vorvick, Kawabe)
 3) New EOM                             (UF, Franzen, Amin)
 4) PMC redo                            (Amin, Savage, Garofoli)
 5) Vent Ends ->                        (Wooley)
      ETM Baffles                       (Traylor, Sellers)
      ETM Re-align w/ PAMs              (Traylor, Sellers)
 6) ISCT1 Floating prep (if necessary)  (Schofield, Hanson, Evans)
 7) SUS Bias Modules                    (Abbott, Fyffe, Weiss)
 8) HAM6 Electronics                    (Abbott, Watts, Frolov)

 Commissioning  --   18 Weeks
-----------------------------------------------
 1) HAM6 controls commissioning         (O'Reilly, Amin)
 1) DC Readout debugging                (Frolov, Kawabe, Hoak, Watts)
    (MICH starts before arms are open)
 2) IFO Locking (on RF)
 3) Full Noise debugging                (re-establish S5 sensitivity)

 Laser Install  --  4 weeks
-----------------------------------------------------
 1) Install                            (LZH, Amin, Savage, Cook, King)
 2) Servo Tune Up                      (Amin, King, Frolov, Franzen)

 High Power / DC Readout Commissioning  -   20 Weeks
-------------------------------------------------------
 1) Noise Hunting                            ---
 2) Highpower RF                       (Abbott, Frolov)
 3) New ASC code                       (Bork, Bogue, O'Reilly)
```

4.2 Hanford

```
 Vent part 1  -   3 weeks
-----------------------------------------
 1) HAM6 flange / window               (Ryan, Worden)
 2) HAM4 telescope re-alignments       (Bland, Gray, Lubinski)
 3) Faraday Isolator                   (UF, Rakhmanov)
 4) ITM Re-alignments w/ PAMs          (Cook, Bland)
 5) ITM Arm Cavity Baffles             (Cook, Bland)
 6) Drag Wipe the MC                   (UF, Gray, Bland)
 7) ISS Pickoff move (part of FI install)
 8) Laser electronics installation (Myers, McCarthy, Savage, Garofoli)

 Pump Down    -   6 weeks
---------------------------------------------
 1) HAM installation                   (Radkins, Gray, Coyne, Landry)
 2) OMC + HAM6 Optics                  (Vorvick, Kawabe)
 3) New EOM                            (UF, Savage, Amin)
 4) PMC redo                           (UF, Savage, Amin, Garofoli)
 5) Vent Ends ->                       (Worden)
      ETM Baffles                      (Cook, Bland)
      ETM Re-align w/ PAMs             (Cook, Bland)
 6) ISCT1 Floating prep (if necessary) (Schofield, Lubinski)
 7) SUS Bias Modules                   (Abbott, Myers)
 8) HAM6 Electronics                   (Sandberg, Abbott, McCarthy)

 Commissioning  --   12 Weeks
-----------------------------------------------
 1) HAM6 Commissioning                 (Landry, O'Reilly)
 1) DC Readout debugging               (Kawabe)
    (MICH/PRC starts before arms are open)
 2) IFO Locking (on RF)
 3) Full Noise debugging               (re-establish S5 sensitivity)

 Laser Install  --  3 weeks
-----------------------------------------------------
 1) Install                           (LZH, King, Savage, Cook)
 2) Servo Tune Up                     (Savage, Garofoli)

 High Power / DC Readout Commissioning  -   16 Weeks
-------------------------------------------------------
 1) Noise Hunting                          ---
 2) Highpower RF                      (Abbott, Myers)
 3) New ASC code                      (Bork, Barker)
```

5 Budget



	Qty	unit cost, $	total for 2 ifos, $	R & D
Power Increase				
EO modulators	6	4000	24000	
Faraday isolators	3	25000	75000	
PSL/IO optics	1	100000	100000	
Laser	3	185000	0	
Infrastructure for laser	2	25000	50000	
Laser controls	2	10000	20000	
PMC mirrors	1	10000	10000	
Subtotal			**279000**	
Vacuum hardware for HAM6 detection				
Isolation plate	2	20000	40000	
Gate valves	4	4000	16000	
Ion pump setup	2	12500	25000	
Turbo pump setup	2	21500	43000	
Windows	4	3000	12000	
Subtotal			**136000**	
Output mode cleaner				
OMC cavity bodies	3	10000	30000	1
OMC mirrors	2	10000	20000	
OMC suspension	2	50000	100000	1
Opto-mechanical HW	2	30000	60000	
Electronics	2	25000	50000	
Subtotal			**260000**	
HAM6 Seismic isolation, single stage ISI				
ISI instruments	2	160000	320000	1
ISI mechanics	2	290000	580000	1
Support structure	2	120000	240000	1
ISI electronics	2	35000	70000	1
Subtotal			**1210000**	
TCS lasers	3	10000	30000	
TCS optics	3	10000	30000	
ITM beam tube baffles	4	7000	28000	
WFS electronics	5	10000	50000	
Bias modules	20	750	15000	
Total			***2038000***	
covered by AdLIGO R&D			665000	
Not covered by AdLIGO R&D			***1373000***	

Figure 7: Hardware Budget for LIGO Enhancements

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A Required R&D

Between now and the middle of 2007, there are many aspects of the design that need to be developed. The following is a list (not comprehensive yet).

A.1 Output mode cleaner

A.1.1 Finalized OMC design

Need to make a full design study of the OMC design, including the following:

- Cavity length
- Finesse
- Topology (4-mirror, planar, bow-tie, etc.)
- PZT: whether or not to have a PZT. Aids in locking, but may be too noisy.
- Thermal actuator: design of a fast thermal actuator.

This is expected to be informed by the prototyping at the 40m lab and also by the work at Virgo as they approach their design sensitivity.

The final design of the OMC for Enhanced LIGO will be done by the OMC design group, a sub-group of the Advanced LIGO ISC group.

A.1.2 In vacuum output table layout

In addition to the main OMC / PZT mirror / DC sensing system being prototyped in the 40m, we expect to also move the dark port wavefront sensor into the vacuum. To operate the in-vacuum sensors we would like to also have camera views from outside the tank which can see inside and not interfere with the SEI system.

Doug Cook will be the lead engineer on the task of designing an optical layout for HAM6 which meets all of our requirements.

A.1.3 In- vacuum RF diodes

The DC photodetectors for the dark port sensing are being prototyped at the 40m. To sense the other length degrees of freedom in vacuum we need to also develop in-vacuum RF

PDs. The current thinking is to bundle this task with the design of the in-vacuum WFS (see below).

A.1.4 In-vacuum wave front sensors

There is currently a design effort to develop in-vacuum, high power, WFS. Rather than develop a whole in-vacuum circuit technology the current approach is to encapsulate each detector in a metal can with an AR coated window and feedthroughs to get the signal out to the control systems. The encapsulated circuit would then operate at atmospheric pressure (using some noble gas tracer). A similar approach is used at LASTI for the in-vacuum seismometers for the Advanced LIGO SEI sub-system.

Rich Abbott has taken on the task of re-designing the WFS electronics and also the new design task of making vacuum compatible RF photodetector designs.

A.2 High Power Laser

Characterization of the new MOPA system is ongoing at LZH and as the Advanced LIGO PSL liaison, Peter King is also interfacing with LZH to ensure there is a smooth and timely handover of the system. Rick Savage has agreed to serve as the Observatory liaison for the lasers and will be working with Peter to make sure all the necessary electronics and infrastructure on the U.S. side is ready before installation starts next year.

A.3 Excess Low Frequency Noise in initial LIGO

Although the LIGO noise budget explains most interferometer strain noise, all three detectors exhibit unexplained noise between 40 and 200 Hz. The noise has been extensively studied and fits into two broad categories: upconversion and mystery noise. The upconversion is characterized by a broad band increase in the 40-200 Hz strain noise correlated with low frequency seismic background. The up-conversion noise appears to be linearly proportional to the test mass actuation force below 10 Hz. The periods of lowest noise suggests that upconversion contributes $\approx 50\%$ of the noise in the 40-200 Hz region of the gravitational wave band. Although there is certainly more than one form of upconversion noise, the dominant mechanism has been identified as an electronic problem lying between the output digital to analog converter and the coil driver output. This source of noise should be eliminated in the next round of S5 commissioning.

Although upconversion is insignificant at times of very low seismic activity, excess noise contaminates the 40-200 Hz gravitational wave band of all three detectors, the so-called mystery noise. No definitive measurements have shown that the mystery noise arises from the same source in all three detectors. Many scenarios have been proposed to account for the noise and several tests have been performed. At this time interferometer tests largely exclude Barkhausen[17] noise, suspension stick-slip noise[18], excess suspension wire loss, and light scattering as the noise generating mechanisms.

The most promising candidate for the mystery noise is related to charge buildup on the test mass surface. Calculations indicate that charge migration on the optic and the nearby support structure can lead to fluctuating electric fields large enough to be observed as test mass motion. This theory may be observationally supported by the decrease in the LLO mystery noise after the release of the statically stuck ITMY optic and the retraction by several millimeters of the Flourel tipped earthquake stops. The remaining noise in the 40 - 130 Hz band (see Figure 6) has the same frequency dependence as before the intervention, implying that charge induced noise may be a problem for the remaining LLO optics as well. As described in Section 3.4.3, the earthquake stops will be reworked during the vent to install the new Faraday Isolator.

Sam Waldman is the lead scientist coordinating the effort to track down and reduce the sources of excess low frequency noise for Enhanced LIGO.

A.4 ISC Beam Stabilization

The Advanced LIGO ISC plan calls for in-vacuum detection of all interferometric signals and active beam stabilization on all ISC beam paths. The candidate actuators are: the fast tip/tilt PZT mirrors currently used to stabilize the beam on the initial LIGO symmetric port tables and also in the 40m DC readout system, and also softer suspended mirrors such as are used in the MIT ponderomotive experiments or as available commercially (e.g. the Newport FSM-320).

The beam stabilization system development will ramp up at MIT over the following year, with Peter Fritschel leading the effort.

A.5 Enhanced TCS

The Enhanced LIGO power increase to 30 W will require an upgrade of the TCS laser system both in power and stability. As shown in Table 1, the required 9.1 W of CO_2 laser power is greater than the 8.3 W available from the current CO_2 lasers. Moreover, to keep the thermoelastic noise 5x below the desired strain sensitivity, the CO_2 lasers' RIN must be better than $1 \times 10^{-7} Hz^{-1/2}$ at 100 Hz. The available 20 W CO_2 lasers have an unacceptably high RIN necessitating an intensity stabilization servo. Assuming 1 nV/rHz of readout noise, the 1 mV maximum signal available from the currently used 10 μm photovoltaic sensors allows stabilization with a RIN of $1 \times 10^{-6} Hz^{-1/2}$, inadequate to reduce the thermoelastic noise below the desired strain sensitivity. According to a study by R. Weiss, photovoltaic sensors are available with which the RIN can be reduced to $3 \times 10^{-8} Hz^{-1/2}$, 30x below the strain noise. Some development will be required to incorporate new sensors, an acousto-optic modulator and an intensity stabilization servo with the existing TCS optical bench and 20 W lasers.

Phil Willems will continue as the lead TCS scientist and will head the effort to make the necessary improvements in time for the Enhanced LIGO program.

A.6 Suspension Thermal Noise

The status of our knowledge of suspension thermal noise remains largely the same as at the time of the writing of T050252[1], with a few exceptions:

- Measurements of the actual suspension wire have been made at MIT[25] yielding values of ∼0.0002 for the internal loss.
- Further measurements of the in-situ violin mode Q's are still consistent with our model of the loss in the suspensions.
- Work is currently underway at MIT to determine if the suspension clamp is indeed a source of excess thermal noise.

So far there is no evidence of excess suspension thermal noise, but we still need to make a better estimate of it. It is projected to be the limiting noise source in the 60-100 Hz region and a more firm number for the noise level would inform our decisions about what to do with the other less 'fundamental' noise sources such as suspension electronics and coupling from the Michelson loop.

In order to motivate a change of the suspension wire or clamping system we first need to establish that its a problem and then to design a solution. Rather than make a decision at this point its best, instead, to continue our efforts to make a better estimate of the noise.

B Initial LIGO Noise in S5

It is critical to the enhancement program that we understand very well the present noise sources in the interferometers. As a design guide we seek to reduce all of the 'technical' noise sources to 1/5 of the more fundamental noise sources (thermal, shot).

Figures 8 and 9 from the automated noise budget plotting program help to illustrate the current understanding.

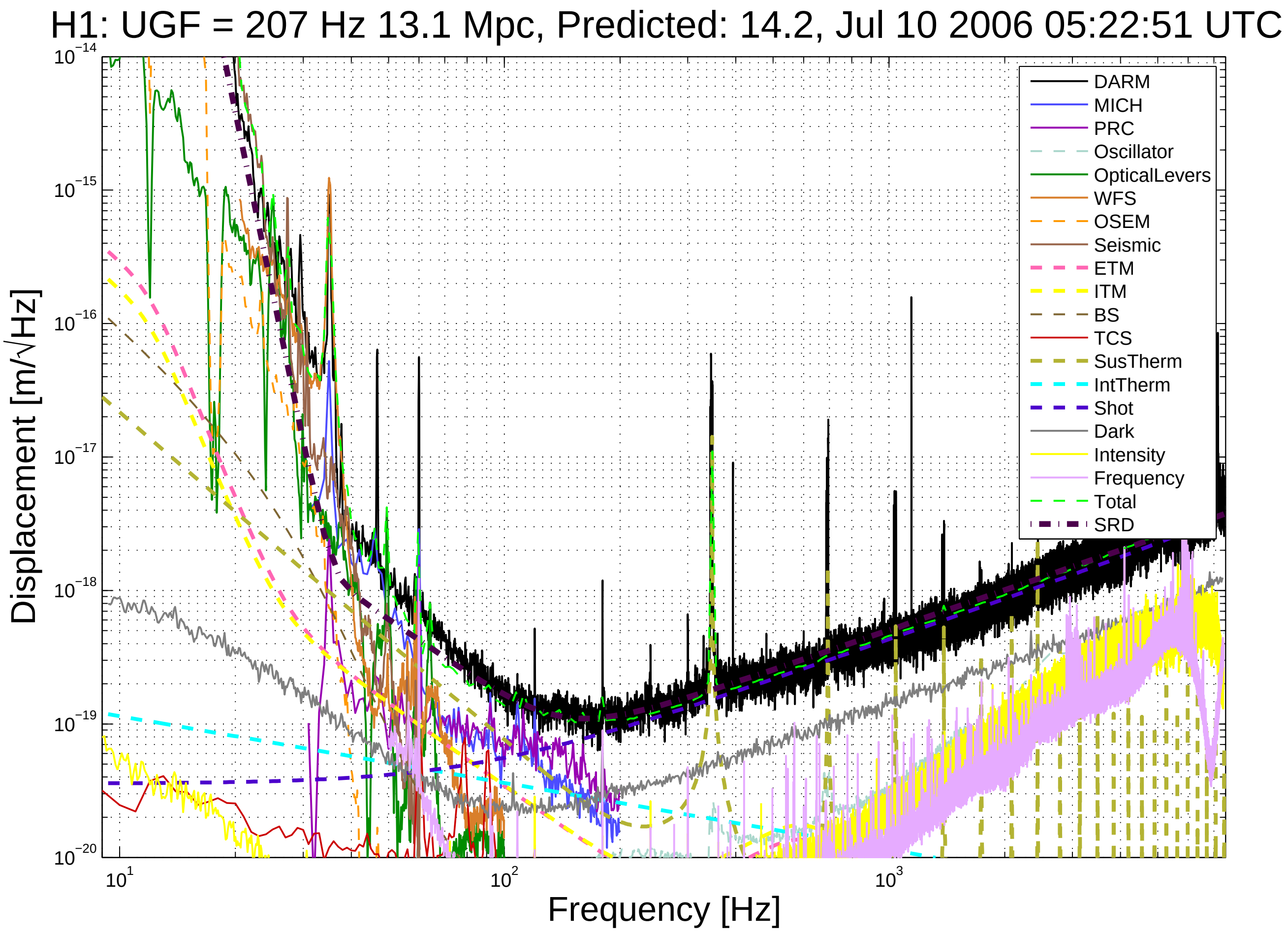

Figure 8: Noise Budget of the Hanford 4K interferometer

B.1 Anomalous Couplings

The laser amplitude and frequency noise couplings measured for H1 and L1 show up above the SRD/10 level; higher than designed. The amplitude noise coupling is almost 10x larger than expected[9] and from the H1 OMC tests we believe it to be 'dirt' effect caused by the large amount of higher order TEM modes present at the AS port. The unexpected, large frequency noise coupling below 100 Hz on L1 looks to be due to cross-coupling through other LSC loops. More investigations are required to pin down whether or not this will continue to be a problem with a DC readout.

B.2 Shot Noise

The shot noise estimate in both the H1 and L1 noise budgets is made in the following way: A 'light bulb' test[29] calibrates the amount of AS_Q counts (from 100-8000 Hz) as a function of DC photocurrent. This calibration, along with the knowledge of the RF sideband to carrier ratio is used to estimate the amount AS_Q noise we get from each photodetector

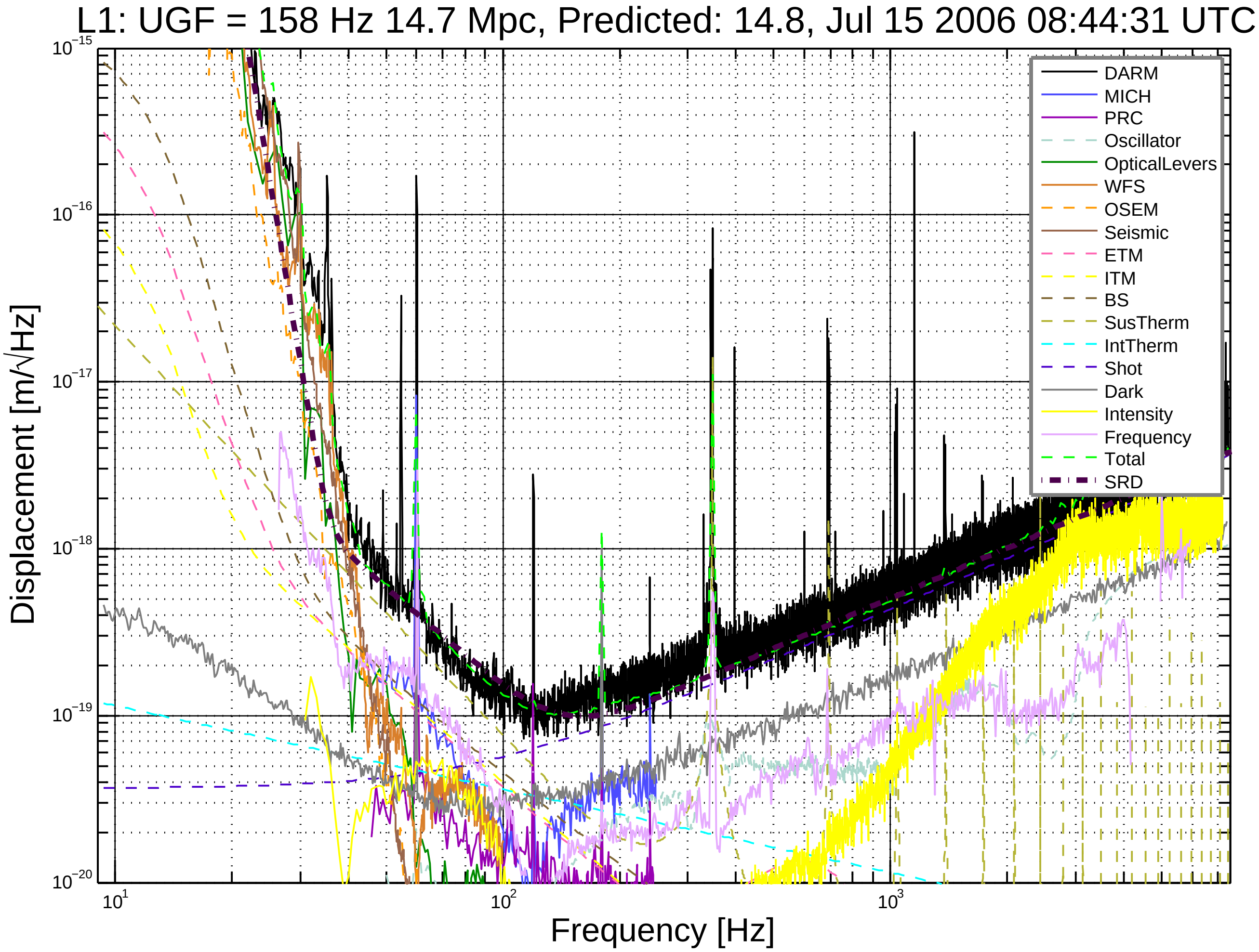

Figure 9: Noise Budget of the Livingston 4K interferometer

in-lock. The final calibration into meters/$\sqrt{Hz}$ is made in the same way as the main strain calibration for the interferometer.

Even so, there is a discrepancy between the measured optical gain of the interferometer and the one calculated from measurements of the field amplitudes at each port. The measured optical gain in Watts/Meter is only 60% (∼70% for H1) of what one calculates (in the plane wave approximation). We assume that the discrepancy is due to a non-ideal overlap between the sideband and carrier modes at the dark port.

C DC Readout

A detailed analysis of most of these noise sources in the existing RF scheme is given in [9].

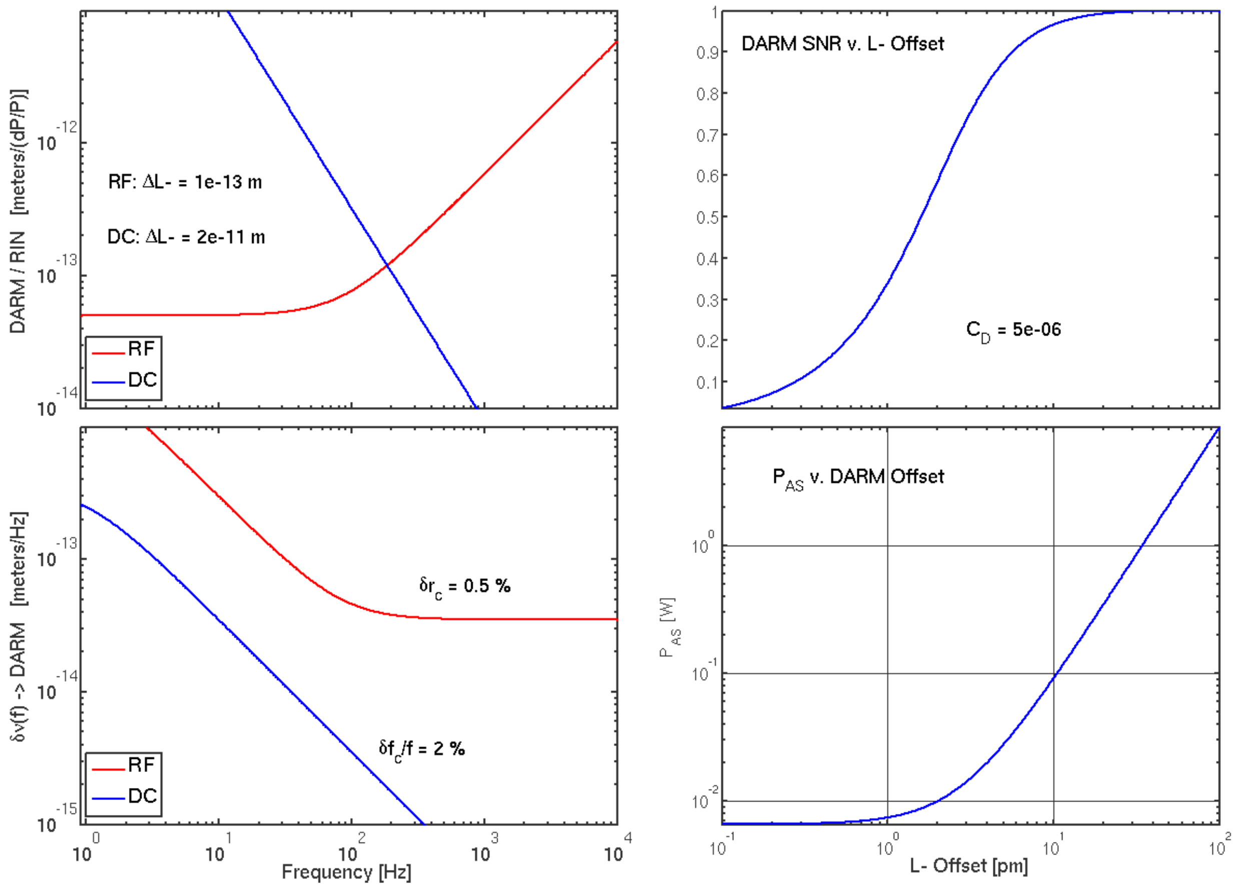

Figure 10: Comparison of laser noise couplings between RF and DC readout for nominal parameters: Laser Amplitude Noise (upper left), Laser Frequency Noise (lower left), Shot noise limited SNR v. L- offset (upper right), DC readout AS port power (lower right)

C.1 Laser Amplitude Noise

In the RF scheme, the laser amplitude noise is stabilized on the PSL table before entering the vacuum. The amplitude noise on the carrier light is low-passed at 1 Hz by the coupled power-recycling / arm cavity. The noise on the RF sidebands passes unfiltered to the dark port and appears as gain modulation of the GW signal.

In the DC scheme, the fringe offset makes a first-order coupling to laser amplitude noise. However, this is only the noise on the filtered carrier since the RF sidebands are rejected by the OMC. For small offsets, the laser amplitude noise coupling is an increasing function of offset (see Appendix C.6).

To the extent that the RF sidebands are not rejected by the OMC (because of a finite finesse) they do contribute to the amplitude noise coupling. In Figure 10, only the carrier contribution is shown. For a modulation depth of 0.3, a DC fringe offset of 10 pm, and an OMC finesse of 500, the coupling above 200 Hz becomes equal to that of the RF w/OMC case.

C.2 Laser Frequency Noise

The laser frequency noise coupling mechanisms are detailed on p.69 of [9]. Since the coupling through the RF sidebands dominates presently, it is expected that the impact of frequency noise on the strain spectrum will be reduced by at least one order of magnitude at all frequencies. The laser frequency noise coupling will then be limited only by the storage time mismatch of the arm cavities which has been measured[9] to be 2% or less on all interferometers.

C.3 RF Oscillator Noise

The residual coupling of the RF oscillator phase noise to the strain output is almost completely removed by going to a DC readout scheme[12]. The phase noise coupling becomes second order; the phase noise couples to the symmetric port I-phase RF signal through the residual Q-phase offset. This second order mechanism comes in below the standard frequency noise level described above.

C.4 Scattering

An analysis of noise due to internal scattering in the OMC has not yet been made but is part of the OMC design study which is going on this year.

C.5 Alignment Fluctuations

Our previous experience[7] with an out-of-vacuum OMC taught us that beam jitter can be a significant noise source. V. Mandic has recently done an analysis[27] of the noise coupling for LIGO assuming we use the OMC output chain being used at the 40m lab. The punch line of the analysis is that a medium bandwidth (∼50 Hz) auto-alignment servo will be sufficient to remove beam jitter from the OMC noise budget.

C.6 Shot Noise

In Figure 10 the shot noise limited SNR as a function of arm cavity offset is plotted. In the case where there is no contrast defect we can, in principle at least, run with a vanishingly small offset. In the real interferometers, however, there is a static TEM_{00} contrast defect which comes about from scatter loss imbalance between the arms. This TEM_{00} defect passes through the OMC and contributes to the shot noise level. Measurements of the frequency noise coupling coefficient at both sites[9] tell us that the contrast defect, C_D, is 5 ppm on L1 and a bit less, 2 ppm, on H1.

We assume that we will adjust the DC arm offset to get ¿95% of the maximum SNR and so the detectors need to handle ∼150 mW of static power.

C.7 Readout Electronics

The noise and dynamic range requirements on the DC readout detection chain should be achievable using using our existing DC photodetector technology (ISS, 40m DC PDs). Figure 11 shows the current L1 noise level but passed through the modeled DC detection chain (using the standard 10 pm offset and an OMC transmission of 100%). Also plotted is the shot noise level from the expected photocurrent and the voltage noise from one of our low-noise DC detector front ends.

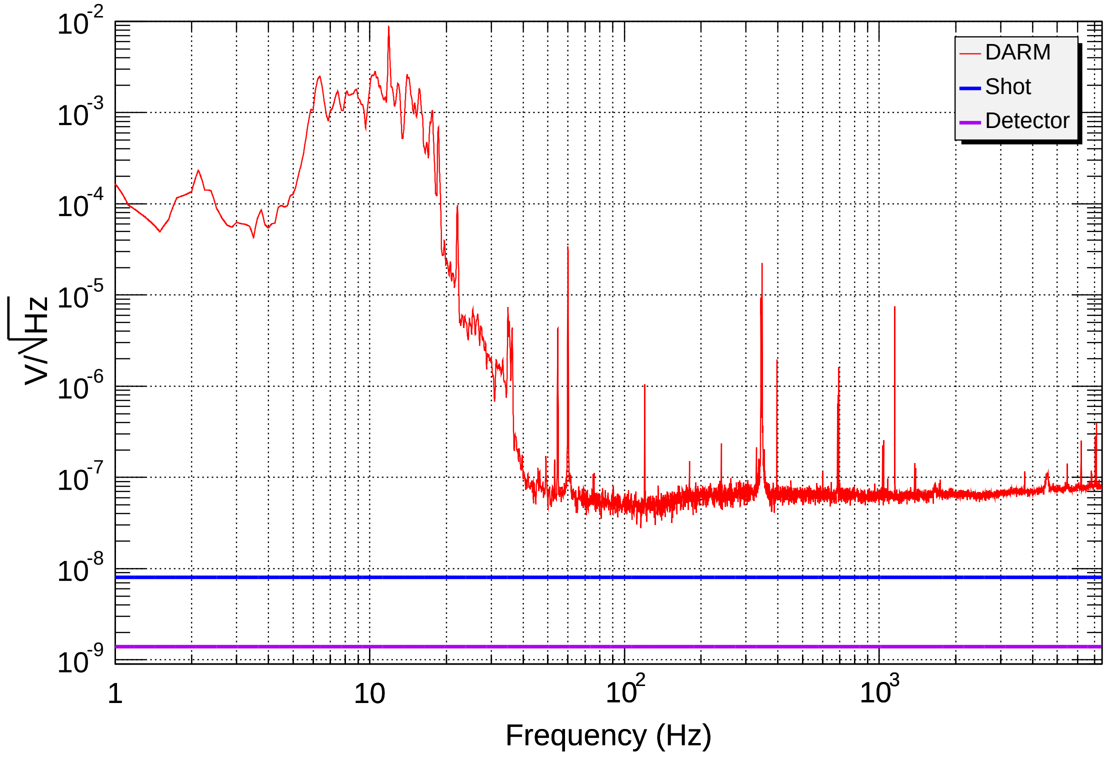

Figure 11: Noise spectra at the DC photodetector front end. (RED) S5 noise curve (in-loop), (BLUE) shot noise from 100 mA, (PURPLE) electronics front-end noise

D Projected Noise Budget

In order to make an estimate of the total strain noise of the interferometer, we have made some assumptions about the various noise sources (this is largely the same as in T050252[1]).

- SEISMIC: No significant improvements of the in-band seismic noise. Remediation of the turbulence in the HVAC system is expected to reduce the excitation by factors of a few in parts of the 5-60 Hz band and reduce some of the upconversion noise (see A.3).
- WFS/OPLEV: No significant change in the angular controls noise is planned other than the standard maintenance level of repairing broken sensors/electronics or slightly increased light level. On average, this will account for a factor of $\sqrt{2}$ improvement in the sensing noise.
- MICH: It is planned to increase the power on the recycling cavity pickoff detector by a factor of 2 (to 100 mA). Since it is in the shot noise limited regime this should buy us a 30% noise reduction.
- Oscillator/Intensity/Frequency: As described in section C, the laser noise contributions should be much reduced by the move to a DC readout.
- SUS Electronics: described above in section 3.4.4. Dominated by current noise from the bias electronics.
- SUS Thermal: Assumed a loss angle in the steel wire of ϕ_w=3e-4 and a vertical beam offset[19] of 1 cm to minimize the pitch thermal noise.
- Mirror Thermal: The Noise Budget currently assumes a internal loss of 1e-7 and coating loss of 2e-4[26].
- Shot Noise: To calculate the shot noise it is assumed that the TEM_{00} contrast defect is 5e-6 and that the transmission of the OMC is 100%.

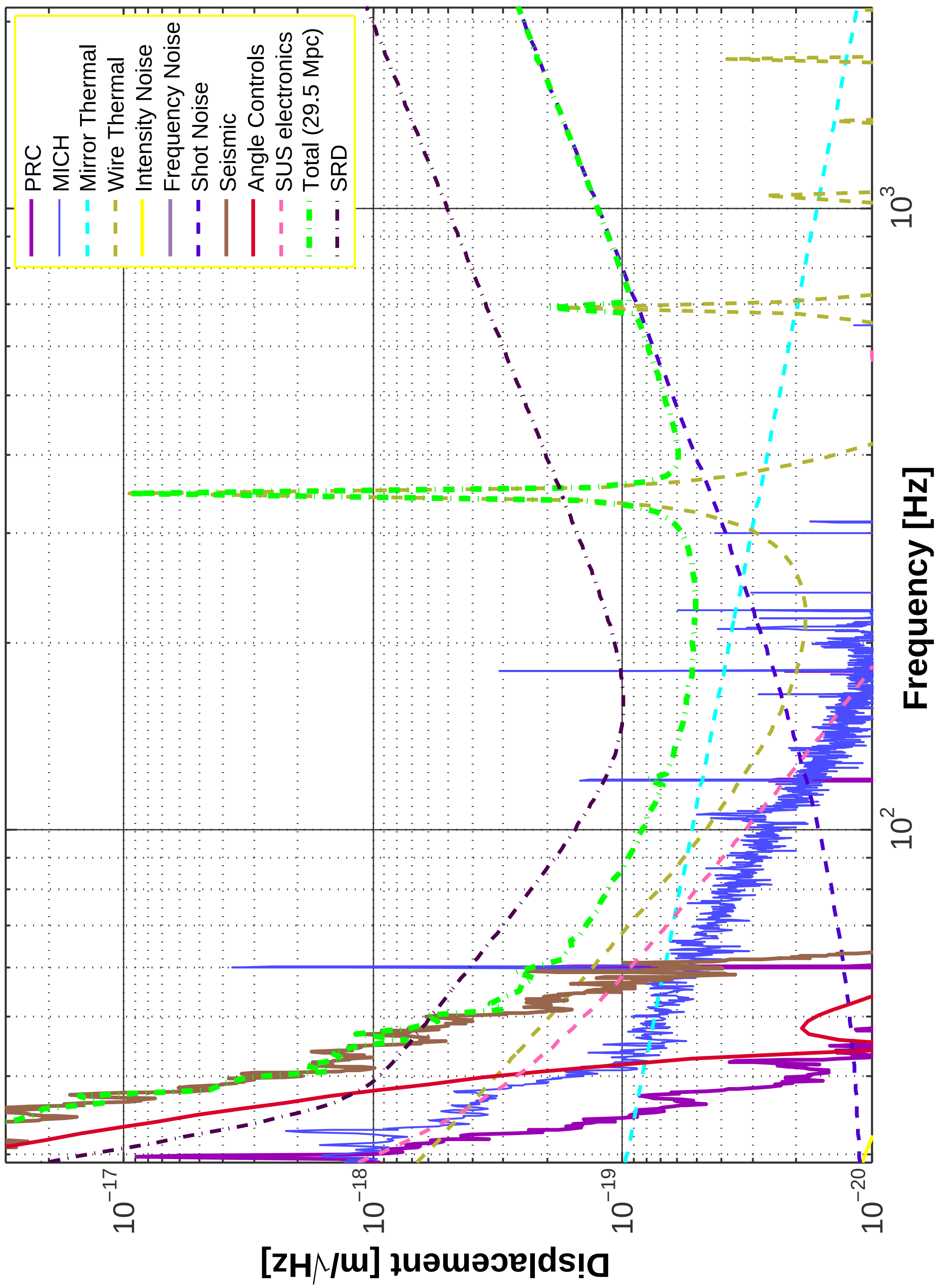

Figure 12: Estimated Noise Budget of the Enhanced LIGO interferometers