LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Scientific Collaboration

LIGO-T0900276-v4 23 July 2009

LSC Instrument Science White Paper 2009

LSC Advanced Detector Committee, for the LSC

Distribution of this document:
Public domain

This is an internal working note
of the LIGO Scientific Collaboration.

California Institute of Technology
LIGO – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834

Massachusetts Institute of Technology
LIGO – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014

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/

1 Introduction

The LIGO Scientific Collaboration (LSC) maintains a research and development program directed toward the improvement of the current generation of LIGO and GEO interferometers as well as toward the development of concepts, prototypes, components, and modeling for future interferometer configurations. Research is conducted broadly along four main themes: novel interferometer topologies and sensing schemes, advanced high power lasers and light, test mass mirror and ancillary optical materials and components, and methods for reducing stochastic forces on the test mass mirrors through suspension and seismic isolation design. These four themes form the basis for the LSC technical working groups (WG) that coordinate the efforts across LSC member institutions:

- The Advanced Interferometer Configurations Working Group (AIC)
- The Lasers and Light Sources Working Group (LWG)
- The Optics Working Group (OWG)
- The Suspensions and Isolation Working Group (SWG)

The intent of the white paper is to provide a synopsis of the current R&D directions of the four LSC instrument science technical working groups. While not exhaustive, the white paper outlines the main current and future research foci of each of the groups.

Instrument science is a broad topic. An obvious part of the effort is in the design, building, and characterization of test systems and prototypes. Another element, of growing importance as we push harder on the envelope of performance, is the theory of materials and precision measurement. As this often requires scientists and skills beyond those of the existing groups, it can be expected that this will be an area of needed growth in the Collaboration to succeed in the larger goal of advancing the field of gravitational wave detection.

Broadly speaking, instrument science research efforts break down into two categories. Near term efforts in each of the WGs are directed toward those aspects of Advanced LIGO which are not yet fully specified or fully understood. The time scale for research projects in this class to bear fruit is anticipated to be over the next three to five years. We do not report Advanced LIGO Project activities in this report, as it is planned, supported, and carried out in a different model than the general Collaboration research program.

Longer term research (with applications beyond the five year horizon) which can be applied to Advanced LIGO as possible upgrades and/or will inform the design of possible third-generation instruments will also be discussed. An overall improvement in the strain sensitivity is clearly attractive for both improved measurement precision of gravitational strain waveforms, and seeing weaker and more distant sources. This will allow detailed comparisons with general relativity, better understanding of neutron star and black hole evolution, and of supernovae. There is a strong scientific motivation to probe gravitational waves in the frequency band 0.1-10 Hz. In addition to bridging the gap between space-based instruments, e.g., LISA (operating below 0.1 Hz) and Advanced LIGO/Virgo (operating above 10 Hz), this frequency band is expected to contain a number of sources that would be otherwise inaccessible. This includes intermediate-mass binaries and black holes (100-10000 solar masses) and majority of known pulsars (about 90% of the known pulsars have frequencies in the 0.1-10 Hz band). This band would also allow a much more sensitive measurement of the stochastic GW background, potentially clear of the astrophysical foregrounds (all of the currently expected astrophysical stochastic foregrounds are outside of the 0.1-10 Hz window). Signals from high-frequency pulsars (700-1000 Hz) contain information about the inner forces of neutron stars. Improvements in this frequency range present a completely different set of challenges compared to the low frequency band.

There is enthusiasm and commitment to create instruments which can realize these observational goals, and the GWIC Roadmap[1] for the future of the field shows the unity of purpose. The LSC intends to start the process of developing a conceptual design for third-generation instruments, and looks forward to collaborating with the European design study for the Einstein Gravitational Wave Telescope (ET).[2] As this work is cross-disciplinary, and also involves observatory siting and other systems issues, it will be pursued by a focus group made up of those interested from all of the 'traditional' instrument science working groups along with those with skills in designing observatory infrastructures and detector networks.

We note that third-generation research will almost certainly play a role in mitigating unforeseen problems in Advanced LIGO, as our experience with initial and enhanced LIGO has shown us.

This white paper represents the current thinking of the LSC technical working groups as of mid 2009. It will undergo revisions periodically as we reassess the needs of LSC instrument science.

[1] Draft at http://gwic.ligo.org/roadmap/

[2] H. Lück and M. Punturo, "Design Study Proposal for E.T. (Einstein Gravitational Wave Telescope)", submitted to the EU Seventh Framework Programme (FP7).

2 Suspensions and Isolation

2.1 Introduction

The research of the Suspension and Isolation Working Group (SWG) is aimed at providing the necessary isolation of the interferometer optics from seismic and mechanical disturbances whilst simultaneously ensuring that the displacement due to thermal noise of the suspended systems is at a suitably low level. To first order we can divide the research into two broad subdivisions, suspensions and isolation, both of which involve mechanical and control aspects. Suspension research involves study of the mechanical design of the suspensions, the thermo-mechanical properties of the suspension materials and suitable techniques for damping suspension resonances and applying signals for interferometer control. Isolation system research involves mechanical design and active control for isolation and alignment. The overall isolation of the optics comes from the product of the two systems.

The initial LIGO detector test masses are suspended as simple pendulums in cages which are bolted to the upper stage of four-stage mass-spring seismic isolation stacks. In addition at LLO, a hydraulic external pre-isolation stage (HEPI) has been installed, between the piers and crossbeams, to provide extra noise reduction between 0.1 and 3 Hz and tidal actuation. At LHO, the original coarse actuation stages remain, together with fine actuators used for tidal actuation in the end stations. Recently some active seismic isolation using the fine actuators has been implemented at LHO's end (and mid) stations.

To meet the more stringent noise requirements for Advanced LIGO, the isolation and suspension system for the most sensitive optics is comprised of three sub-systems: the hydraulic external pre-isolator (HEPI) for low frequency alignment and control, a two-stage active isolation platform designed to give a factor of ~1000 attenuation at 10 Hz, and a quadruple pendulum suspension system that provides passive isolation above a few hertz. The final stage of the suspension consists of a 40 kg silica mirror suspended on fused silica fibres to reduce suspension thermal noise.

As a precursor to Advanced LIGO a set of incremental changes have been implemented, known as Enhanced LIGO, as part of which an Advanced LIGO HAM Internal Seismic Isolation System (ISI) is installed in each observatory to support the AdvLIGO design output mode cleaner (OMC) whose suspension is a double pendulum for enhanced isolation. Work on commissioning and optimizing the HAM ISI, including the development of tools to simplify commissioning of the hardware and the control systems is ongoing, reducing risk in the Advanced LIGO project. In addition the testing of the OMC suspension has given and will continue to yield useful experience with a multiple suspension system prior to the installation and commissioning of the other more complicated triple and quadruple suspension systems in Advanced LIGO.

Most of the R&D for all the Advanced LIGO isolation and suspension sub-systems is well underway and final designs have been chosen. There is still some ongoing R&D of immediate relevance to Advanced LIGO, which will serve to reduce commissioning time or may prove to be of use in enhancing aspects of the performance of the currently conceived Advanced LIGO designs. This work is discussed in section 2.2. However we are now moving into a period of increased focus on conceptual designs and laboratory research for future, more advanced detectors. The technology development toward 3rd generation detectors is discussed in section 2.3.

2.2 R&D to support Advanced LIGO commissioning and upgrades

2.2.1 Isolation systems

2.2.1.1 Current status and ongoing work

The hydraulic pre-isolation stage (HEPI) is in place at LLO and is being replicated at LHO in preparation for the Advanced LIGO installation. LIGO requires two variations of the in-vacuum platform, one for the BSC chambers and one for the HAM chambers. The design includes a two-stage active platform for the BSC and a single-stage platform for the HAM. The two-stage BSC ISI system is currently being tested at the LASTI facility at MIT. Controllers for that system and its integration with the quadruple suspension prototype and the HEPI system are a centerpiece for the plans for Advanced LIGO. A pair of the single-stage HAM ISI systems for Advanced LIGO have been commissioned at the observatories as part of Enhanced LIGO. A third HAM ISI system will also be built and delivered to LASTI toward the end of 2009 for further development and Advanced LIGO integration testing.

2.2.1.2 Tilt/horizontal coupling and advanced seismometers

One of the limits to the performance of seismic isolation systems is the coupling between ground tilt and horizontal motion of the isolation platforms. This is fundamentally caused by the inability of a horizontal sensor (or a passive horizontal isolation stage) to distinguish between horizontal accelerations and tilts in a gravitational field. This tilt-horizontal coupling causes a variety of problems at the microseismic peak (~0.16 Hz), and is a basic limit to the performance of the systems at these frequencies. The Advanced LIGO test-mass isolator prototype is now limited by this coupling at low frequencies, and an external sensor could be easily integrated into the system to reduce amplification of low frequency noise. The performance limitation increases the amount of control needed at the pendulum, and complicates lock acquisition. Several methods of addressing tilt issues are being pursued. First, we are developing sensors to measure the rotational acceleration of the ground. Currently we are investigating pairs of differential vertical seismometers, whose spatial separation would allow us to measure ground tilt, and a suspended bar tiltmeter, which is presently undergoing preliminary tests and will also yield results on losses in different materials. It is also important to investigate other types of sensors, such as active (laser) or passive ring-gyros, or deep-set level references which compare the tilt of the technical slab of the observatory with the level determined by a pair of geological references buried several meters below ground. Development of tiltmeters is an area in which collaboration with Virgo colleagues is also underway.

2.2.1.3 Suspension point interferometer

It is also possible to improve the performance below 1 Hz with an auxiliary system which reduces the differential motion and tilt of the various optical tables in the detector. This type of approach has been discussed for many years, and is traditionally called a 'Suspension Point Interferometer'

(SPI), i.e., an interferometric sensor which measures between the points which suspends the arm mirrors. The system we are investigating is slightly different; we plan to control the relative motion of the optical tables, which is why this system is called the Seismic Platform Interferometer. The relative motion of the tables for this system will need to be measured in at least 3 degrees of freedom, namely length, pitch, and yaw. This will allow the detectors to be mounted securely to the table, and will also allow the benefits to be shared by multiple suspensions on the same table, a common situation on the HAM optical tables.

It should be noted that improved rotational sensing and the seismic platform interferometer are complementary approaches to the low-frequency control issue, and having both would be better than having either by itself. It is also important to realize that since the optical tables for Advanced LIGO are controlled in all 6 degrees of freedom, once the new SPI or tilt sensors become available, they can be incorporated into the existing control system easily, because the seismic tables will not require modification.

2.2.2 Suspensions

2.2.2.1 Excess thermal noise from clamps and break-offs

At present, initial LIGO, while having nominally reached its design sensitivity, appears to be limited in the 40-100 Hz band by an as-yet undetermined noise source. At its minimal level, this noise has a frequency dependence similar to suspension thermal noise. Research suggests that the initial LIGO wire loop suspensions exhibit excess loss, possibly from clamps or due to stick-slip effects at the break-offs, causing suspension thermal noise which could be making a significant contribution to the excess noise seen in initial LIGO. Investigations are thus currently ongoing on alternative wire clamping methods in order to better understand and reduce this noise. This work is risk reduction for the suspensions in Advanced LIGO for those optics whose noise requirements do not require the use of fused silica suspensions such as the HAM small and large triple suspensions and the beamsplitter suspension. If wire clamping methods which yield lower thermal noise suspensions employing metal wires can be developed, they could replace the existing approach as a future upgrade to Advanced LIGO.

2.2.2.2 Multiple pendulum suspensions - mechanical and control aspects

The quadruple suspension design for the test masses in Advanced LIGO is based on the triple pendulum suspensions developed for GEO 600. The suspensions for the most sensitive mirrors (those hanging in the BSC chambers) are being built in the UK by a team supported by STFC funding. Other optics suspensions are the responsibility of the US part of the suspension team, and consist of triple and double pendulums. R & D is well advanced, with an all-metal prototype quad suspension and an all-metal triple suspension already fully characterized at LASTI. Studies of full Advanced LIGO noise prototypes including in particular the test mass quadruple suspension noise prototype to be tested in conjunction with the BSC ISI active isolation platform are underway, with assembly, installation and operational checks plus development of novel control strategies for local and global control. Some risk-reduction characterization, with potential for incremental design improvements, will continue.

2.2.2.3 Development of monolithic final stage

Characterization (strength, dimensions, mechanical loss) of fused silica fibers as suspension elements, produced using both oxy-hydrogen and laser-based pulling techniques, is well underway, as is development of welding techniques and silicate bonding techniques including characterization of associated losses. There has also been a lot of work carried out on the ear shape and fibre shape including the neck region. ANSYS modeling has been used to localize the bending energy and to optimise the fibre shape to minimize thermoelastic noise. Assembly and testing of a full monolithic suspension as part of the quad noise prototype discussed above will take place later this year.

Further understanding and characterizing of losses in silica fibres including investigations of non-linear thermoelasic noise and of surface losses could lead to improvements for possible application to upgrades to Advanced LIGO. An increase in strength could allow reduction in cross-section and in vertical bounce frequency, enhancing isolation.

2.2.2.4 Violin mode damping

The silica fibre suspensions will have very high Q violin modes (of order 10^8). Such high quality factors make stable control of the interferometer with wide bandwidth more challenging and also lead to long ring-down times after any mechanical excitation. Lower Q values (of order 10^6) lead to easier operation, and work is underway to realize an active damping scheme using an optical sensor and feedback to the penultimate mass of the suspension, to be tested on the quad noise prototype at LASTI; this system is planned to be part of the AdvLIGO baseline.

2.2.2.5 Creep noise

Some sources of detectable gravitational waves are expected to impulsive, short, rare events in an extremely large body of data, and so characterization and reduction of "background" transients of technical origin is important. Some work on looking for non-thermal noise originating in the fused silica fibres has been carried out with no non-thermal noise being seen at modest sensitivity (insufficient to exclude it as a significant noise source for AdvLIGO). Work has been done to study the noise associated with the violin modes of the silica suspensions in GEO 600 and further work is underway to extend these studies by modeling to put upper limits on the expected noise in Advanced LIGO. No work as yet has addressed transients coming from higher up the suspensions and/or from the silicate bonded test-mass ears. Direct experiments to characterise the level of and/or put upper limits at a meaningful sensitivity level to potential non-Gaussian transient events associated with the Advanced LIGO suspension system are challenging. However new ideas for carrying out such experiments are encouraged.

One approach which will be pursued to observe the impulsive releases of energy or acoustic emissions (“creak effect”) is to strain the element statically while also driving the element through a large amplitude motion at low frequency below the measurement band, while interferometrically measuring the element at high sensitivity in band (above 10 Hz). By large amplitude motion we mean much larger (100-1000 times) than the out of band motions estimated through modeling as described in section C above. We will when possible drive the large amplitude low frequency motions in a common mode fashion between two identical devices under test while measuring the noise which will be uncorrelated between the two elements.

2.2.2.6 Low noise cantilever blade springs

Development of fused silica blade springs for improved vertical isolation compatible with lower thermal noise than that obtained with maraging steel blades is an attractive option to explore for possible upgrades to Advanced LIGO and future interferometers. Glassy metal and ceramic blades may also be considered to reduce fractal noise if that is shown to be a problem, see 2.2.2.7.

2.2.2.7 Low Frequency Noise

Studies of the behavior of maraging steel cantilever springs have uncovered low frequency noise which may be of fractal origin (LIGO-P0900028-v2). This noise, particularly visible in low frequency oscillators, can result in instabilities, hysteresis, and 1/f noise, and may extend to higher frequencies. Further work will study the extent of noise spillover at higher frequency, and the possibility of using different materials and material treatments to reduce this noise at higher frequency.

2.2.2.8 Control aspects and different payloads

Lock acquisition of the Advanced LIGO detectors is a challenging problem, due to the addition of the signal recycling mirror, the increased finesse of the arm cavities, and the long time needed for core optics to reach thermal equilibrium. Studies of ways to extract better information to set the detector at its operational condition would be of great value to the project. The seismic platform interferometer is an example of this type of device, because it allows some measure of the relative motion of the optics, even when the main gravitational wave interferometer is not running. Studies of additional ways to gain information about the state of the detector could also lead to shorter lock acquisition times and improved duty cycles. Future seismic isolation systems will probably have the same basic system-level function, to reduce the relative motion among payloads in vacuum tanks. However the payloads will change and may include cryogenic systems, larger suspended mirrors that could employ all reflective optics or suspensions that need to dissipate more heat.

2.3 R&D Towards Third Generation Detectors

Several noise sources all increase steeply as frequency decreases, combining in the Advanced LIGO design to form a noise 'wall' at approximately 10 Hz. Thus for any future detector beyond Advanced LIGO, improved performance at frequencies below 10 Hz will require research and development targeted at three areas in particular:

a) reductions in suspension thermal noise

b) improved seismic isolation

c) reduction of 'Newtonian' or 'gravity gradient' noise

Forces due to time-varying electric charge is dealt with in the section on Optics. Strawman designs for future interferometric detectors have taken baselines of increased test mass size to reduce the effects of radiation pressure (up to several hundred kg), with suspensions fabricated of alternate materials (e.g., sapphire or silicon) possibly cooled to cryogenic temperatures to reduce thermal noise. These strawman designs, along with the need to reduce gravity gradient noise and increase seismic isolation, thus point towards a set of areas to which current lab R&D can be targeted.

2.3.1 3rd Generation Isolation systems

2.3.1.1 Very low frequency passive isolation

An alternative approach to isolation, using very low frequency passive isolation, has seen application in e.g., Virgo and TAMA. Elements of this approach may be applicable to 3rd generation instruments as an effective extension of the pendulum suspension isolation, especially for cryogenic instruments where managing the thermal conductivity of the isolation system is important. The R&D on the passive system to date has improved our understanding of mechanical systems significantly and has led to the discovery of an additional mechanical noise mechanism (see 2.2.2.7), which needs to be studied for future lower frequency observatories, and possibly to fully understand the low frequency noise of Advanced interferometers. An isolator based on the this design is being developed for the 10m Hannover test facility, and is being considered for injection detection benches in Advanced Virgo.

2.3.1.2 Newtonian coupling

One of the low-frequency noise sources expected to be a challenge is direct gravitational coupling between the test mass and moving mass in the local environment, sometimes called the Gravity Gradient or Newtonian Background noise.

Newtonian (or gravity-gradient) noise refers to fluctuations in the local gravitational field due to the motion of the nearby masses. Such fluctuations will pull back and forth the interferometer mirrors, increasing the overall noise floor of the detector. Several theoretical studies have shown that the dominant contributions to this noise source are due to surface seismic waves and atmospheric density fluctuations. These two components appear to be similar in magnitude, and may become a limiting factor for Advanced LIGO at low-frequency (~10 Hz). Moreover, this noise source is expected to become increasingly important at frequencies below 10 Hz: at 1 Hz the theoretical expectation for the seismic gravity gradient contribution (strain equivalent) is in the vicinity of $10^{-20}/\sqrt{\text{Hz}}$. Hence, a suppression by a factor of 1000 (or larger) is required in order to reach the strain sensitivity of Advanced LIGO scale ($10^{-23}/\sqrt{\text{Hz}}$) at this frequency.

To subtract the noise from our gravitational-wave channel we would need to form a feed-forward matrix, by a type of singular value decomposition that would relate the environmental noise to the fluctuating gravitational forces being felt by the test mass. This method can be employed to an online feed-forward (directly driving the test mass) or by using linear regression on the gravitational-wave readout channel.

One of the priorities for the third-generation detectors is to probe frequencies below 10 Hz. Consequently, detailed studies of the Newtonian noise are needed.. Such studies should be performed both on the surface (potentially enhancing the performance of second-generation detectors) and underground (informing the design of potential third-generation detectors). We summarize below some of the directions to be explored.

2.3.1.2.1 Surface

The most promising approach for suppressing Newtonian noise for surface GW detectors is to design an array of instruments (seismometers, barometers etc.) measuring the motion of the ground and air, and use its signals to move the interferometer mirrors so as to cancel the motion due to the Newtonian noise. Several studies are needed to assess the feasibility of this approach:

- Develop an array of seismometers to study the modal structure of the seismic waves on the surface, and to measure the correlation length of the seismic noise as a function of frequency.
- Develop a model that would use the above measurements as input to produce an estimate of the Newtonian noise due to the seismic motion. Such a model would determine the size of the array necessary: area to be covered, spacing between instruments, number of instruments and their sensitivity requirements etc.
- It is currently not clear how large the bulk contribution of the (underground) seismic waves is as compared to the surface seismic waves. Consequently, it is not clear whether underground seismic stations are required in the instrument array. The above measurements and model should address such questions.
- A similar effort should be pursued to address atmospheric fluctuations. This includes a monitoring array as well as modeling of the atmospheric density fluctuations.
- The above studies may require R&D projects to improve sensitivity of the monitoring instruments (such as seismometers), as well as studies of the optimal design for the chamber and the building hosting the interferometer mirrors.

2.3.1.2.2 Underground

There are several potential advantages for building underground GW detectors (as compared to the surface). Forces on the mirrors due to atmospheric density fluctuations are reduced; local disturbances (such as humans and their incessant activity) are much reduced and controllable; the seismic noise is expected to be reduced, with the suppression factor depending on the frequency, depth, and the rock structure. The speed of sound (and correspondingly the seismic wavelengths) underground is much larger than on the surface, implying kilometer-scale correlation lengths in the 0.1-10 Hz band. This opens the possibility of having correlated gravity gradients across the entire detector, resulting in a suppression of this noise source. It also implies that an array of seismometers needed for the active suppression of Newtonian noise could be significantly smaller.

While potentially promising, each of the above arguments needs to be quantified. Again, several research directions are needed:

- Start developing an array of seismic stations underground (preferably in multiple locations) to understand the dependence of the seismic noise amplitude, correlation length, and modal structure, on depth, frequency, and rock composition and structure.

- Such studies should be complemented with optical strainmeters, tilt-meters, dilatometers etc, to further understand the modal structure of the seismic noise.
- Pursue R&D to improve the sensitivity of the above instruments if needed.
- As in the surface case, develop a finite element model that would use the above measurements as input to produce an estimate of the Newtonian noise underground. Such a model would determine the size of the array necessary for the active subtraction: volume to be covered, spacing between instruments, number of instruments and their sensitivity requirements etc. The model should include effects such as surface reflection, scattering off of density fluctuations and fault lines etc.
- Study the effects of the cavity size and shape.

2.3.2 3rd Generation Suspensions

A range of issues appear at first analysis to be worthwhile to pursue. In general, this starts with a program of collecting the present knowledge on the subject and making models and simulations. Small scale experiments follow to allow the utility to be evaluated and the correct path established if interesting. We list some paths currently in exploration.

2.3.2.1 Silicon suspensions

Silicon has attractive thermal and thermo-mechanical properties making it a strong candidate for the suspension elements in future detectors possibly operating at cryogenic temperatures to reduce thermal noise. It is also conductive which may have advantages for controlling charging effects (discussed elsewhere). Development and measurement of suitable suspension flexure elements, including studies of the optimum material, thermal noise properties, and the geometry and assembly of elements including methods of bonding to test masses are being pursued. Analysis techniques include the use of FEA to study the various contributions to thermal noise such as surface effects. Investigation of fabrication techniques, properties of silicon- silicon bonds such as strength and thermal conductivity and thermo-mechanical properties of silicon, for example as a function of doping, are examples of areas which can be addressed.

2.3.2.2 Attachment techniques

Alternative attachment techniques to silicate bonding may be investigated, e.g., to eliminate shear stress in any contact point in the mirror suspensions.

2.3.2.3 Larger masses

Considerations of how to suspend large (several hundred kg) masses, possibly at cryogenic temperatures, are important to pursue. Particular challenges of a suspension system for such masses include maintaining low suspension thermal noise and high seismic and mechanical isolation, incorporating actuation, and integrating such a system into a detector. Fabrication of such large masses is also an issue (considered elsewhere in this document).

2.3.2.4 Cryogenics – suspension and isolation aspects

Studies of systems with suspension elements of suitable design and dimensions to provide an efficient path for required heat conduction while still maintaining good thermal noise and mechanical isolation performance should be carried out.

2.3.2.5 Cryogenics – radiative cooling

Operation at cryogenic temperatures poses formidable challenges including heat extraction from the cooled test masses, required both under steady state operation and for cooling from room temperature in a reasonable time. The system needs to work without adding noise or short-circuiting the mechanical isolation. In the steady state, the circulating power may be in the range 0.5 to 1 MW, and with anticipated coating losses of 0.5 to1 ppm, power loss in the arm coatings is of order 0.3 to 1 W per optic. For cooling a reasonable estimate is between 2 and 100 W of heat conduction from the test masses to the cold environment.

Studies are underway of a novel method of heat removal: near-field radiative coupling between two objects: one hot and one cold. The basic idea is that many thermal fluctuations in the hot object do not couple to radiation; instead, they produce evanescent fields outside the object. If a cold object with appropriate properties is introduced into this evanescent field region, energy is transferred, cooling the hot object. This approach is potentially capable of removing more than 200 W from an advanced-LIGO test mass. The heat transfer can be greatly enhanced using a small gap but this is accompanied by force coupling and this effect needs to be taken into account. Experiments to explore this method of heat transfer are underway with a first goal to observe and characterize the heat transfer in the near-field regime. The second will be to determine the effects of coatings on the heat transfer, and to attempt to optimize the coatings for maximum transfer with spacing around 0.5-1 μm.

3 Optics Working Group – LSC Research white paper

The Optics Working Group (OWG) of the LSC pursues research related to the development and implementation of optical components for ground-based gravitational wave detectors. This includes work on optical components to be used in Advanced LIGO, to better understand their behavior during commissioning and operation, possible upgrades to particular subsystems of Advanced LIGO, and longer term research into ways around significant limitations in current detectors for third generation detectors.

3.1 Research on Improving Advanced LIGO Optical Performance

The basic design for the Advanced LIGO interferometers was presented in the LSC White Paper on Detector Research and Development [ref Gustafson, et al] in 1999. Since then, the design has significantly matured [ref Advanced LIGO Reference Design, LIGO-M060056]. Within the OWG, two important milestones have been reached; the selection of *fused silica* as the Advanced LIGO mirror substrate material and the selection of titania doped tanala/silica as the Advanced LIGO coating. There remain numerous areas of research in the OWG to understand better what can be expected from Advanced LIGO optics and to make incremental improvements in the planned optics for possible upgrades to Advanced LIGO.

3.1.1 Optical coating research

The high-reflection (HR) coatings on the Advanced LIGO test masses must satisfy a number of performance criteria including low absorption, low scatter, high uniformity, designed reflectivity at both 1064 and 532 nm, low mechanical loss, and low thermo-refraction. Of these, mechanical loss and optical absorption carry the most risk but also the greatest opportunity to improve sensitivity.

Doping the tantala layers with titania has been shown to reduce mechanical loss. Doping titania with silica also promises to improve Brownian thermal noise. Titania-doped tantala/silica has been selected for the Advanced LIGO coatings with silica-doped titania/silica as a fallback. The use of alternative dopants in tantala and/or different high index materials is being explored as part of the research program to understand mechanical dissipation in coatings. A trinary alloy of titania/tantala/silica as the high index material may allow for benefits from each material. Both hafnia and niobia with silica, titania, alumina, etc as dopants are worth exploring as well. New treatments and designs, rather than materials, also promise improved coatings. These include carefully chosen annealing processes and the use of rugate (continuously varying indices) and/or very thin layer coatings. The effects of any new materials and/or techniques on properties other than mechanical loss, including optical absorption, Young's modulus, thermo-refraction, and index also need to be studied to insure any new coating doesn't sacrifice too much (or at all) in other areas in the attempt to improve Brownian thermal noise.

There is currently minimal theoretical guidance on what coating materials might have improved thermal noise. To help address this, there is an effort underway to develop molecular level models of amorphous dielectric oxides to develop an understanding of mechanical loss. Silica is the best material to start with, as there is a fairly extensive literature on molecular modeling of silica and the cause of mechanical loss is well understood. After success with silica, further models of other dielectrics can be used as input when choosing coating materials. Detailed work on the dependence of mechanical loss on temperature, temperature history, and frequency in coating materials would also help to better understand the source of the mechanical losses.

There has been progress in developing better theoretical models of thermal noise, given the experimental values of parameters like mechanical loss. The effect of the finite size of mirrors, long overlooked or treated by numerical estimates, has been determined analytically. Theoretical efforts to look for correlations in different aspects of thermal noise, that could be tweaked to cancel out, are also underway. This effort has stressed the importance of understanding the loss angle associated with shear modulus, which has not been measured directly by experiment. The effects of diminishing optical power on thermal noise from coating layers closer to the substrate remains to be described in detail and explored.

Since the mechanical loss in the coatings typically scales as the total thickness of the more lossy material, reducing this thickness while maintaining the optical properties will reduce thermal noise. Constrained numerical optimization codes have been shown to produce high reflectivity coatings while reducing the volume of high index materials by as much as 20%. Thermo-optic noise from thermoelastic and thermorefractive effects is included in this optimization. The mechanical loss of the low index (silica) material takes on a larger role for thickness optimized coatings, as optimization typically makes the high index (titania-tantala) contribution equal to the low index. Such an optimized design is planned for use in Advanced LIGO. Greater understanding of mechanical loss in thin film silica is crucial.

Absorption of the interferometer circulating light in the coatings will result in thermo-elastic distortions of the optics and ultimately limit the circulating power. When coupled with the bulk absorption in the input test mass, this leads to significant surface deformation of the test masses as well as bulk thermal lensing in input test masses. Coating absorption levels of 0.3 ppm have already been reported on undoped tantala/silica coatings. Both the titania-doped tantala and silica-doped titania coatings have been shown to have absorptions at or below 0.5 ppm. Any improvements beyond this level will make thermal compensation easier.

Thermorefractive (dn/dT) and thermoelastic (dL/dT) effects in coatings are noise sources that is driven by the same (coherent) temperature fluctuations. Recent reanalysis has shown that there is a partial cancellation between thermorefraction and thermoelasticity in coatings, so the total noise is not expected to be as high as previously feared. A value for dn/dT for ion beam deposited tantala is not available in the literature, so experimental efforts are ongoing to measure it. Existing data from the Caltech-based Thermal Noise Interferometer (TNI; high displacement sensitivity interferometer testbed) can be used to set upper limits on thermo-optic noise in tantala/silica and titania-doped tantala/silica coatings, and additional mirrors for the TNI can be coated with any new coatings that show promise. Should results indicate that this thermo-optic noise will be a limiting noise source, it may be necessary to try to develop coating materials with improved dn/dT values. More complete understanding of thermorefractive noise is crucial when predicting the likely sensitivity of upgrades to Advanced LIGO and future detectors.

Concerns with scatter in operating interferometers (including initial LIGO and Virgo) indicate there may be a need to develop coatings with lower intrinsic scatter. Examination of initial LIGO and potential Advanced LIGO coating with a scatterometer will be valuable to determine whether the problem is with the substrate polish or the coatings, whether new coating materials have the same or different coating properties, and whether the coating vendor affects the scatter. Detailed planning and development on clean handling and installation of the optics is important to keeping the scatter at the level set by the coating. This has relevance for Advanced LIGO procedures as well as for future instruments.

The Thermal Noise Interferometer has directly measured coating thermal noise from tantala/silica, titania-doped tantala/silica, and thickness optimized tantala/silica coatings. Continued verification of the validity of the Q measuring program by directly measuring coating thermal noise from promising coatings is invaluable to our understanding of coating thermal noise. Work to directly measure coating thermal noise in the final Advanced LIGO coating before coating and installing the Core Optics is currently in progress. Plans are underway to measure thermo-mechanical properties of candidate coatings, including thermal expansion and thermal conductivity, for better prediction of thermo-optic noise. The TNI, as the unique low-displacement-noise suspended mirror testbed in the community, may also be useful for studying noise sources like charging noise, suspension thermal noise, or new noise sources that we come to appreciate as important during commissioning. The design of the TNI is under study for alternative approaches to yield the desired information in simpler instrument configurations.

3.1.2 Fused silica test mass research

The OWG determined for Advanced LIGO that fused silica was the preferred test mass material substrate for that instrument. It is possible that reduced coating thermal noise (due to improved coatings) could make thermal noise from silica substrates a significantly contributing noise source in an Advanced LIGO upgrade. Investigations are planned to examine the effects of mechanical loss versus annealing parameters, including peak temperature, ramp down time, and dwell time. In addition, possible tradeoffs will be explored between optical absorption and mechanical loss. Spatial absorption profiling will also be carried out to determine the observed level of substrate absorption inhomogeneity, necessary to understand to the level of thermal compensation that will be needed.

3.1.3 Thermal compensation research

It will be necessary to apply thermal compensation methods to stabilize the recycling cavity and maintain the radii of curvature of the test masses against thermo-elastic distortion effects resulting from circulating light absorbed in the coating and subsequent heating of the test masses. Both bulk and spatially-resolved compensation will be required. For Advanced LIGO, thermal compensation will be applied to compensation plates located in the recycling cavity.

To minimize the effects of these distortions the optic's temperature must be maintained more uniformly in the radial direction. One way this could be done would be to coat the barrel of the optic with a thin layer (a few microns) of a metal that reflects IR such as gold. Modeling indicates this would greatly reduce the radial temperature gradient in Advanced LIGO. Adding a gold barrel coating to the optics would have implication for other aspects of the design, notably thermal noise, charge mitigation, and parametric instabilities. Measurements of the mechanical loss of a thin gold coating indicate that the gold coating can be applied without adversely affecting thermal noise. It should be noted that any gold coating applied to the barrel for thermal compensation purposes will not reduce the optics modal Q's enough to cause significant improvement in parametric instability performance. Tests of a gold coatings interaction with possible charge mitigation schemes, including UV, are underway. Results of these tests might require follow-ups with other materials and/or coating methods or with additional modeling. This technique may be ready for use in Advanced LIGO or may be part of an upgrade.

A scanning (or more generally a directed-beam) thermal compensation system that can vary the compensation profile in real time without injecting noise into the signal band would be very valuable, either as an enhancement for Advanced LIGO or for third generation detectors. This will require research on carbon dioxide lasers, to reduce noise and possibly boost power, and potentially on measurement and control issues. In addition, by moving to shorter wavelengths it might be possible to develop MEMS or other technology based spatial light modulators to allow a programmable heating beam profile.

3.1.4 High power effects in Advanced LIGO

The build-up of parametric instabilities in the arm cavities and possible contamination of the high reflection coatings related to the high intensities present in the arm cavities are potential issues. The Australian Consortium has developed a high optical power facility at Gingin in Western Australia designed to develop methods for controlling instabilities associated with high optical power. Potential solutions to high power problems can be prototyped here before inclusion in Advanced LIGO or its upgrades.

At high optical powers, the radiation pressure force of scattered high order optical cavity modes can couple strongly to the mechanical modes of the test masses, resulting in a parametric instability. Unfortunately, the requirements for high sensitivity are commensurate with the conditions under which parametric instability occurs. Using finite element methods, it is possible to develop a quantitative understanding of the problem by modeling the modes and parametric gain for different test mass configurations, as well as investigate methods for mitigating the instabilities. Measurements on suspended test masses are needed to obtain realistic 'as built' test mass Q values to establish the net gain for the instabilities. Adding tuned mass dampers to the barrel of the test masses and/or using feedback to the electro-static drive also show promise for controlling parametric instability. In addition, spatially-resolved radiation pressure feedback on the mirror surfaces is being contemplated. Experiments investigating parametric instabilities are underway at the Gingin facility and at MIT. Moreover, at MIT studies are underway to incorporate small mechanical dampers on the test mass that can eliminate the parametric modes altogether without increasing the thermal noise.

3.1.5 Modeling thermal effects in Advanced LIGO

The development of realistic models of the performance of the interferometers is also crucial to achieving the performance goals of Advanced LIGO and its upgrades. Efforts are focused on the

SIS (Static Interferometer Simulation) model, using FFT-based Huygen's principle light propagation, for investigating how the interferometers will perform when operating at full power.

A new version of the FFT-based SIS program is being developed to simulate the full Advanced LIGO optical system using C++. It is designed to be flexible enough to simulate details of optical setups, like compensation plates and finite aperture and thickness of optics, and to include all necessary physical effects, like thermal aberrations of various kinds and resulting field distortions and losses. Cavities are locked using an algorithm close to a locking scheme used in the experiment, so that the comparison between the simulated result and the experimental data can be compared more easily. The signal sidebands are simulated in the locked cavity so that the performance can be realistically evaluated. This way, the program will be useful during the design stage, as well as during the commissioning phase.

Although the SIS FFT code is in principle more powerful than modal models based on sets of Hermite- or Laguerre-Gauss modes, the modal model codes are faster, easier to debug, the results are easier to understand, and they are very useful to interpret the SIS FFT code. Consequently, it is important to continue the development and support of thermal modeling codes such as Melody or other modal models.

3.1.6 Diagnostics for Advanced LIGO optics

Each of the mirrors in Advanced LIGO will have slightly different absorption characteristics and therefore will react differently when subjected to laser powers projected for Advanced LIGO. It is useful to develop methods that allow for remote monitoring of the condition of a test mass or beam splitters using optical wavefront sensing methods. Off-axis Hartmann wavefront sensing has been developed for measuring the absorption-induced wavefront distortion in the test masses and beam splitter. The measured noise limited sensitivity of the Hartmann sensor itself is $\lambda/15{,}000$, and recent experiments have measured wavefront changes smaller than $\lambda/3000$. When applied to off-axis tomographic measurements, the current measured accuracy is $\lambda/120$, limited by factors other than the Hartmann sensor itself. Further research is aimed at improving this performance.

3.1.7 High power optical components

Electro-optical modulators and Faraday isolators are essential parts of every interferometric gravitational wave detector. Apart from the laser gain medium, they are the components which experience the highest power densities in transmission in the entire interferometer. RTP based electro-optical modulators have been developed and tested for Advanced LIGO. Although long-term tests at the 200W power level are still pending, it is expected that these crystals can withstand the power without degrading over time. Similarly, Faraday isolators with internal compensation schemes to reduce thermally driven depolarization and beam quality degradation have been developed and tested for Advanced LIGO, also waiting for a long term test with the 200W Advanced LIGO prototype laser.

Advanced LIGO upgrades might need even more laser power to increase its high frequency sensitivity or reduce the need for power recycling. Future detectors might operate at a shorter wavelength to reduce coating thermal noise or use a longer wavelength to take advantage of silicon.

Any of these changes requires a targeted research program to identify the best optical materials and to develop sufficient compensation techniques to eliminate thermal lensing and laser power induced birefringence and optical damage in these essential components.

3.1.8 Charging of test masses

Surface charge may build up on the test masses through a variety of mechanisms, including contact with dust (particularly during pump down) and/or the earthquake limit stops, removal of First Contact used to keep the optic clean during transport and handling, as well as cosmic ray showers. There is already evidence in initial LIGO that charging of the optics has occurred from hitting earthquake stops.

Gaussian noise due to surface charging can be described by a Markov process [R. Weiss T960137-E]. The result depends strongly on the correlation time of the deposited charge, with a smaller fluctuating noise for longer correlation times. This is being measured using scanning Kelvin probes operated in vacuum which measure the magnitude and distribution of surface charges and their rate of motion across a sample. Current results indicate that the correlation times depend on the type of silica, but can be very long for very clean samples, leading to current estimates that this need not be a significant noise source for Advanced LIGO. Continuing work will focus on examining a variety of silica types, different cleaning and handling methods (including ways of applying and removing First Contact), and optics with coatings. Various coatings will be characterized as they are developed in the coating research program. Understanding what sensitivity limits might come from charging and how this may depend on cleaning, handling, and/or material choices is crucial for Advanced LIGO. Depending on results, it may prove an important area of research for upgrades. Charge may also interact with the electro-static drive planned for use in Advanced LIGO causing noise or reduced effectiveness of the drive. Modeling has been started to study this, but experimental work would be valuable to better understand the role of charge on the electro-static drive. There is some concern about possible noise from dielectric polarization of the fused silica which could arise from interactions with the electrostatic drive. Both experimental and theoretical work is planned on polarization noise. Calculations have also been carried out to estimate the force noise that might be expected from Coulomb interactions between charge accumulations on the test mass and various components in the suspension system. The earthquake stops being the closest to the test mass surfaces are of greatest concern for most issues with charge on the optic.

Shining UV light on *in situ* optics is being investigated as a way to mitigate charge buildup. This involves testing UV LEDs, developing AC driver electronics, and doing experiments to determine if the UV can cause harm to the optics or their coatings. Coated optics are tested by subjecting them to UV light for days to weeks at a time, then are re-measured for optical absorption and mechanical loss. Results on tantala/silica optics indicate that UV can cause increased optical absorption but the levels of UV exposure needed for charge mitigation will likely not harm the optics. Follow-up work is in progress using titania doped tantala/silica coatings as well as on whether different cleaning and handling techniques influence the effect of UV on the optics and their coatings. Experimental work on low energy ion guns as a way to mitigate charge without the need for UV exposure is also beginning. This work is performed in conjunction with the Suspensions Working Group.

It would also be useful to directly measure noise from charging, to confirm both the Weiss Markov-process noise model and the parameters found from the Kelvin probe work. Existing low noise prototypes, like the TNI at Caltech, might be used to explore this potential noise. Another possibility will be to use a low noise torsion pendulum, as has been used in LISA and laboratory gravity experiments, to study charge noise. A torsion pendulum most sensitive at low frequency, typically about 10 mHz, where charge noise is expected to be highest. Torsion pendulums have been used successfully for noise investigations in the past. For charge studies, the torsion pendulum will need to be made entirely of an insulator, likely fused silica, which is a departure from previous experience. The LSC group at the University of Washington, which has experience with torsion pendulums through LISA and other research programs, is beginning a program to study charging noise important to LIGO.

3.1.9 Variable reflectivity signal recycling mirror

One possible improvement to Advanced LIGO would be to install a variable reflectivity signal recycling mirror (VSRM), to permit more flexible tuning of the signal recycling cavity. This would make it easier to tune the sensitivity of Advanced LIGO to different types of sources; narrowband pulsars, neutron star binary inspirals, etc., and/or to optimize given other instrumental shortcomings like optical loss. Focus is currently on a control system that can work for a full resonant sideband extraction interferometer with a VSRM. Modeling efforts are underway to determine the practicality of this concept. Demonstration of the performance of a VSRM on a prototype interferometer will likely be necessary before it could be considered for an upgrade to Advanced LIGO. This work is performed in conjunction with the Advanced Interferometer Configurations Working Group.

3.1.10 Investigation into sources of non-Gaussian noise

Non-Gaussian noise sets a limit on Burst Gravitational Wave searches, and there are suggestions that aspects of the optics may contribute to non-Gaussian noise. Sources of such transients must be characterized and eliminated during the design, installation, and/or commissioning phases. One possible source of such transients is motion of coating imperfections within the beam due to test mass motion. Electric charge buildup and stress relief in silicate bonds, welded silica-silica joints, and/or coatings will also be explored as sources of transients. Theoretical or modeling efforts on non-Gaussian events would be very beneficial to better understanding the causes and cures of this noise. In addition, measuring non-Gaussian noise in a tabletop interferometer or other sensitive instrument may help better understand the sources and nature of this noise. It will also allow diagnostic and modeling software to be developed and tested, which can then be applied to the LIGO detectors. This work is performed in conjunction with the Suspensions and Detector Characterization Working Groups.

3.2 Optics Research and Development for Third Generation Detectors

The OWG also conducts directed research for future gravitational wave detectors beyond Advanced LIGO. While this research is more speculative and long term than that directed toward Advanced LIGO and simple upgrades, it is clear that research on optical components for future ground-based interferometers must begin well in advance of any complete conceptual design.

3.2.1 Beam Shaping

Mirror thermal noise is one of the fundamental factors limiting the sensitivity of gravitational wave detectors. A Gaussian beam profile is not the best shape to average over thermal fluctuations and different, carefully chosen shapes could allow for sensitivity improvements.

Non-spherical mirrors, shaped to support flat intensity ‘mesa’ profile beams, have been designed and fabricated using specialized coating techniques. These mirrors are being tested on a dedicated interferometer to assess ease of mode-matching and locking. Recent efforts have shown that the tilt sensitivity of the fundamental mesa mode agrees with expectations. We aim to extend this study, producing useful alignment correction signals via the wavefront sensing technique. The Sidles-Sigg tilt instabilities must also be examined. In addition, continued modeling will examine how thermal effects alter the mode profile in a detector arm cavity and help develop thermal compensation strategies. One option involves depositing a static thermal compensation profile to mitigate these effects.

Modeling is being carried out on Gauss-Laguerre and other optical modes that show promise for reducing thermal noise. Gauss-Laguerre modes may avoid some of the instability issues that cause concern with mesa beams. There has also been modeling of the effects of different beam shapes on parametric instabilities. Further modeling and experimental testing will be necessary to truly evaluate the potential and limitations of these beam shapes.

3.2.2 Development and characterization of novel optical materials

The OWG is investigating alternative materials to fused silica for use as test mass substrates, especially for use in low temperature detectors Both silicon and sapphire potentially offer superior performance at cryogenic temperatures and/or at particular frequency bands. Different substrate materials, operating temperatures, and laser wavelengths may also require and/or allow for different coatings that must also be studied.

For silicon, efforts have focused on acquiring and fabricating cylindrical test specimens and investigating their mechanical properties as a function of doping. Studies of silicon properties for different crystal orientations should also be started now. In addition, silicon cantilever micro-resonators with resonant frequencies in the sub-kHz range have been fabricated to explore dissipation mechanisms in a regime where thermoelastic effects are significant. Surface loss effects are also emphasized by the large surface-area to volume ratio of the micro-resonators. Preliminary experiments measuring the dissipation have been carried out and reveal disagreement with theoretically predicted loss. Silicon is also a potential coating material at 1.55 microns and will need to be studied as a thin film.

Recent efforts have yielded information about the mechanical and optical properties of sapphire, methods for growing and processing large sapphire blanks, and ways to achieve high homogeneity, low absorption sapphire. Studies on annealing for improved optical absorption have been extended to elucidate further details of the kinetics of the out-diffusion process. Gathering experimental data at low temperature is important to predict the performance of cryogenic sapphire test masses. Room temperature sapphire is also a potential mirror substrate for detectors optimized at higher frequencies.

It is vital to investigate the performance of the optical coatings for cryogenic mirrors as a complement to the research on cryogenic mirror substrates. To take advantage of novel new substrates with improved low temperature performance, we need to characterize the performance of the current coating technology at low temperatures and explore new technologies which are compatible with the new substrate materials and have good optical and mechanical loss properties. Thin silicon cantilever samples are of particular interest as substrates for use in the study of coating losses at low temperature. This type of cryogenic experiment has the potential to yield significant information about the dissipation mechanisms in coatings, through their behavior as a function of temperature. Identifying the root cause(s) of mechanical dissipation in coatings is a crucial step in developing improved techniques for reducing coating loss, which could be of considerable interest for allowing enhanced performance for advanced detectors. A cryogenic optical loss measurement system that can be used as a diagnostic probe of absorption is also available in the LSC.

Understanding the optical loss of silicon if used as a transmissive optic at 1.5 microns is also a useful area of research. The high thermal conductivity of silicon could significantly reduce the effects of thermal loading of transmissive components if the optical loss is low enough. Understanding the temperature dependence of light absorption along with all other thermo-optic and thermo-physical properties will be important. The change to 1.5 micron light will also impact other optical components in the interferometer, including Faraday isolators and modulators. Silicon might also be used as the high index material in coatings. Research will be required to develop suitable components if a change in wavelength is considered. Silicon mirrors and suspension elements have an advantage of being conductive thus control of charging effects may be easier to implement. Nonetheless, charging will need to be investigated since doping and especially coatings can influence the charging dynamics.

Finally, the potential downside of cryogenic mirrors is the strong possibility of contamination through condensation on the surfaces. Methods will need to be developed to (i) mitigate the level of contamination in cryogenic mirrors, (ii) quantify the magnitude and type of contaminants, and (iii) if necessary, clean contaminated mirrors *in situ*. This work is performed in conjunction with the Suspensions Working Group.

3.2.3 Cryogenic Mirror Coatings

It is vital to investigate the performance of the optical coatings for cryogenic mirrors as a complement to the research on cryogenic mirror substrates. The thermal noise of the optical coatings is the fundamental limit for the Advanced LIGO interferometers in the middle of the detectors' frequency band. A simple scaling argument would imply that the thermally driven noise of the coating would decrease as the temperature decreased, but measurements of silica, tantala, and titania doped tantala show that the loss of the material increases at low temperatures, and so the total noise of the current coating technology is worse at cryogenic temperatures than at room temperature. To take advantage of novel new substrates with improved low temperature performance, we need to explore new technologies which are compatible with the new substrate materials and have good optical and mechanical loss properties.

Mechanical loss measurements of coating materials at low temperature are also a valuable way to explore the microscopic causes of internal friction. Identification of Debye loss peaks allows for association of mechanical loss with particular molecular motions, like bond stretching or bending. This understanding, coupled with theoretical and modeling work on coating mechanical loss, is becoming very important to the effort to reduce coating thermal noise in future detectors.

3.2.4 Directed Radiative Cooling

A way to compensate for heating of the interferometer mirrors is to extract the heat directly. This can be done without direct contact to the optic by exposing the parts of the mirror surface that absorb interferometer beam power to a nearby cryogenic surface. By controlling the amount of cryogenic surface, its temperature, and the baffling between it and the mirror, a cooling profile with good match to the likely mirror heating profile can be produced. A preliminary experiment at has demonstrated the principle of this technique.

3.2.5 High efficiency grating development and characterization

All-reflective interferometers using diffraction gratings as optics avoid problems associated with the transmission of large laser powers through optical substrates. High finesse optical cavities have been demonstrated using small gratings. The challenge will be to scale up the optical aperture to what is required for a large detector. In addition, absorption by the grating surface will distort its surface profile, possibly resulting in changes in the beam profile as well as power-dependent changes in the diffracted beam shape and efficiency. Although some modeling has been done, these effects have yet to be seriously investigated. Investigations of mechanical loss in gratings are needed to verify thermal noise levels. Contamination issues are more problematic for diffraction gratings. This work is performed in conjunction with the Advanced Interferometer Configurations Working Group.

3.2.6 Low loss nonlinear optical materials for squeezed light interferometry

Squeezed light injection has been proposed as a method for increasing the sensitivity of interferometers and beating the standard quantum limit. Several groups have already demonstrated squeezed light interferometers, and squeezing has been demonstrated down to frequencies as low as 10 Hz. Nevertheless, squeezing requires careful management of interferometer losses. Efforts to achieve 10 dB squeezing will require, among other things, an understanding of the loss mechanisms in nonlinear materials (e.g. MgO:LN and PPKTP) to better inform improved methods for fabricating lower loss nonlinear crystals. This work is performed in conjunction with the

Advanced Interferometer Configurations Working Group. One of the main loss mechanisms is the Faraday isolator used to inject the squeezed vacuum. Further reductions of the losses in Faraday isolators would improve the performance of squeezed light interferometer.

3.2.7 Composite masses

Increasing the mass of the test masses reduces the standard quantum limit. Beyond a certain size, however, it is impractical to fabricate monolithic masses. Using large masses made as a composite of multiple, smaller pieces can circumvent this problem. Non-cylindrical mass distributions could also be used to increase the total mass and total angular moment of inertia without increasing the optical pathlengths within the substrate. The larger translational and angular moments of inertia would reduce the radiation pressure noise and the eigenfrequencies of the Sidles-Sigg instability. Thermal noise issues related to mechanical loss from the interfaces will have to be resolved. A similar design strategy can be used to reduce parametric instabilities where additional masses would be added to intentionally reduce the Q of modes, but would have to minimize effects on thermal noise. Experimental work on tuned mass dampers to reduce parametric instability has been started.

3.2.8 Shorter Wavelength Light

One way to reduce coating thermal noise is to simply make the coatings thinner. This naturally occurs if a shorter wavelength of light is used in the interferometer. Finding materials with suitable optical (absorption, scatter, thermo-refraction, etc) properties at the new wavelength will be one important challenge for the optics working group. The higher energy photons are a particular concern for absorption as they can more easily form color centers, which has proved problematic in past work with green light. Any optic with transmitted light (coatings, input test masses, beam splitter, Faraday isolator, modulators, etc) will have to be developed and tested carefully. This work is performed in conjunction with the Light Sources Working Group.

3.2.9 Coating-less or coating-reduced optics

There are ideas to get around coating thermal noise using corner reflectors, Brewster angle mirrors, or short Fabry-Perot (Khalili) cavities as end mirrors. Corner reflectors and Brewster angle mirrors would allow for no coatings to be needed and Khalili cavities would allow for much thinner coatings than conventional mirrors. Experimental work is needed to test some of these concepts for practical limitations. A bench experiment has been done forming a cavity with one Brewster angle mirror and one conventional mirror on fixed suspensions to see if a high finesse cavity can be formed. Follow on work with suspended mirrors will be necessary to evaluate the mechanical stability of such a system. Plans are being developed for the new prototype interferometer in Hannover Germany to test Khalili cavities as a way of reducing coating thermal noise. This work is performed in conjunction with the Advanced Interferometer Configurations Working Group.

4 Lasers and Light Sources

With the progress in prepared light sources (squeezed light and squeezed vacuum) and their application, we have chosen to add ‘Light Sources’ to the scope of this Working Group. This provides a home for this research with its intimate relationship to the lasers.

4.1 Advanced LIGO Pre-Stabilized Laser - Background

The development of the Adv LIGO prestabilized laser system (PSL) is effectively finished. A four stage Nd:YVO amplifier system is used to increase the 2W power of a Nd:YAG non-planar ring-oscillator (NPRO) to 35W. An injection locked Nd:YAG end-pumped rod system was chosen as the high power oscillator. An output power of more than 200W was demonstrated in a linear polarized single spatial and frequency mode with such a laser system. The laser is being developed and built by the GEO group in Hannover (Laser Zentrum Hannover (LZH) and Max-Planck-Insitut für Gravitationsphysik / Albert-Einstein-Institut AEI). The goal of the current development phase is to improve the spatial beam profile, the thermal management and the stability of the system. Furthermore actuators for the laser stabilization concept are tested and a computer control system including automation is being designed.

The frequency stabilization concept of the Adv LIGO PSL is very similar to the initial LIGO PSL concept. Most of this system can be copied and only the feedforward control from tidal common mode mirror motion to the laser frequency needs further attention. Spatial filtering of the 200W beam with a rigid spacer ring cavity will be used to bring the higher order mode content of the laser beam down to an acceptable level. The most demanding part of the laser stabilization is to match the relative power noise requirement of $2*10^{-9}$ / √Hz at a Fourier frequency of 10Hz. A level of $5*10^{-9}$ / √Hz was demonstrated in a test setup using an NPRO as the laser source and further work is required to transfer the stability to the laser beam downstream of the suspended modecleaner in AdvLIGO.

The AdvLIGO PSL design, incorporates a Diagnostic BreadBoard (DBB) that allows to measure temporal and spatial laser fluctuations as well as the higher order mode content of the laser under test. This DBB is fully developed and will serve as a useful diagnostic tool not only of the AdvLIGO PSL in operation but as well for all current and future laser development work.

In summary the development of the AdvLIGO PSL is well underway. Only very little R&D work will be required to solve the remaining open questions.

4.2 Third Generation PSL

The laser sources required for third generation laser interferometric gravitational wave detectors depend strongly on the optical configuration chosen. All reflective interferometers have a much higher power handling capability than standard designs with transmissive optics. Sagnac type interferometers need a laser source with low temporal coherence whereas layouts with optical cavities require a high frequency stability of the laser source. Coating thermal noise considerations might require a shorter wavelength of the laser light whereas interferometer with transmissive silicon optics require lasers with longer wavelength. The preferred spatial beam profile might not be a fundamental Gaussian distribution but rather close to a flat-top profile or a higher order

Laguerre Gaussian mode. Even though thermal loading of the interferometer might limit the useful power level in the interferometer, an increase in the laser power might allow that one abandon the power recycling mirror. Most topologies would benefit of the injection of squeezed vacuum into the dark port of the interferometer.

Therefore the research on lasers for third generation gravitational wave interferometer will cover a broad range of wavelengths and temporal coherence.

4.2.1 High power concepts – Yb:YAG

At this time the Nd doped YAG gain medium is the best choice for 100 W class gravitational wave interferometers. However, in the future if kilowatt class lasers become necessary Yb doped YAG, which lases at 1030 nm, could replace the Nd system because of its higher efficiency, lower quantum defect, better thermal management and potentially longer-lived laser diode pumps. Its main disadvantages are that it is a quasi-3-level system and thus more sensitive to increased temperatures within the gain medium, and that it has a much lower pump absorption coefficient. There is a substantial commercial interest driving the development of both Yb lasers and their pump diodes for very high power applications.

4.2.2 High power concepts – slabs, rods

Different concepts are proposed to produce lasers with power levels of several 100W and to amplify these systems into the kW region. The main concerns are the thermal management in the gain material and to reduce beam aberrations.

One way to reduce aberrations is to use a zig-zag beam path to average over the thermal gradient in the laser crystal. Edge-pumped slab geometries can be combined with conduction-cooling techniques which avoid vibrations introduced by cooling fluids in conventional layouts. Off-axis zig-zag end pumping combined with undoped sections of the slab offers a scheme to deliver the pump light into the slab. A rectilinear zigzag duct allows pumping at normal incidence and homogenizes the pump light prior to slab entry. This concept together with a stable-unstable resonator design allows scaling of the slab in the direction orthogonal to the cooling and to the laser zigzag mode plane. One of the main challenges in using slabs is to avoid parasitic beam paths with high gain.

Simulations and experimental work on the zig-zag slab systems needs to be continued. Especially the scalability of the concepts needs to be demonstrated at intermediate power levels and simulations have to be performed towards the kW level. If the interferometer design indicates that kW power levels will be required for third generation interferometers the power scaling has to be demonstrated towards the kW region and these lasers need to be used in tests of optical components and long term tests of the laser system itself.

Efficient birefringence compensation can reduce problems caused by depolarization and by defocusing. Hence the power range in which rod geometries can be used is extended into the several hundred watt range. An appropriate lens system and a quartz rotator is used to image one laser crystal into a second one while rotating tangential polarization directions into radial and vice versa.

In addition to dealing with effects caused by the thermal gradients, there are several ideas to reduce these gradients. By the use of so-called multi-segmented laser rods, the maximum peak temperature of an end-pumped laser rods or slab can dramatically be reduced. For example, in a three-times segmented rod the temperature peak compared to a homogenous doped rod can be uniformly distributed to three peaks. Therefore, the effects of nonlinearities which cause aberrations can be reduced without increasing the overall thermal lens or the birefringence. To reduce the overall head load in laser media the pump wavelength can be changed from 807 nm to 885 nm which reduces the quantum defect and therefore the overall heat load by more than 30%. Core doped rods can be used to achieve an easier and more stable fundamental mode operation. These rods are comparable to a double clad fibre where only the inner core of the rod is doped and the outer core is used as a waveguide for the pump (similar as for the off-axis end pumped slabs). As the gain is only present in the doped inner core of the rod this concept can be compared to mode selective pumping with the advantage that no high brightness pump source is required.

4.2.3 High power concepts – amplifiers

Optical Fiber amplifiers have a high potential to offer single-frequency output at higher efficiencies and at lower cost than solid state amplifiers at similar power levels. Until several years ago diode-pumped fiber amplifiers were limited to power levels of several watts due to the unavailability of high power single-mode pumps and due to parasitic nonlinear effects in the fiber such as stimulated Raman scattering and stimulated Brillouin scattering. The introduction of large mode-area double-clad fibers has enabled output powers of single-mode fiber lasers to exceed 1 kW while retaining excellent efficiencies. The large core in large mode-area fibers decreases the average intensity in the fiber, thereby increasing the threshold of nonlinear processes. The large inner cladding of the double clad fibers allows high power multi-mode pumps to be coupled into the fiber. Bending losses can be used to ensure that the output remains single-mode despite the large size of the core. Fiber amplifiers are currently under investigation by several groups in the LSC. A system with 150 W of output power with a good output beam profile (92% in TEM_{00}) has been demonstrated. The optical-to-optical efficiency of the system with respect to incident pump power is 78% for a 195 W pump source. A good polarization ratio of about 100/1 was achieved. Based on these promising results, experiments should continue to scale the output power of these fiber amplifier systems to higher power levels. The maximum continuous power handling capability of fiber lasers using large area mode and photonic crystal fibers should be studied. This research has to be accompanied by technology studies to protect the critical glass-air interface by for example using a silicate bonded flat at the fiber end to allow the beam to expand before it meet this interface. Furthermore the nonlinear effects need to be studied when the MOPA is pumped with a stabilized master laser with small linewidth. More investigations are required on the reliability of fiber amplifier and their temporal and spatial noise performance.

Very promising results were obtained by the Virgo group in Nice on all-fiber systems combining the creation, modulation and spatial filtering of laser systems. Further research in this direction might lead to a much simplified combined laser/modecleaner system for future gravitational wave detectors.

4.2.4 High power concepts – adaptive optics

To convert distorted laser beam profiles into the Eigenmode of the power recycling cavity (no matter whether this is a Gaussian TEM00 mode, a higher order Laguerre Mode or a mesa-like beam profile) either static or dynamic wave front corrections systems or passive filtering will be required. For higher power levels intrinsic problems are expected with the filtering method and hence dynamic adaptive beam correction methods should be designed. For example, a Shack-Hartman Sensor and a deformable mirror have been developed.

4.2.5 High power concepts – alternative wavelengths

Laser sources with at different wavelength might be required for third generation detectors to reduce fundamental noise or to allow for different test-mass materials with better properties at either room temperature or cryogenic temperatures. Reducing the laser wavelength allows the reduction of the thickness of the coating layers and subsequently reduces coating thermal noise. Increasing the wavelength to 1550 nm allows the use of silicon substrates as transmissive oprical components like the inboard test masses. Lasers which emit directly in the visible are several gas lasers and dye lasers but their efficiency, reliability, controllability and noise performance rule them out as suitable lasers for gravitational wave detectors. In case the interferometer design requires tunability or several closely spaced wavelength Ti-Sa lasers could be chosen either at their fundamental wavelength (650 – 1070 nm) or in a frequency doubled layout. Frequency doubling or even tripling of high-power near-infrared lasers is a more promising option to provide a high power sources at shorter wavelength. An attractive approach is the external second-harmonic-generation (SHG)) in quasi-phase-matched ferroelectric materials such as MgO-doped periodically poled LiNbO_3 (MgO:PPLN), MgO-doped periodically poled stoichiometric LiTaO_3 (MgO:sPPLT) and periodically poled KTiOPO_4 (PPKTP). Green power levels of 16 W have been demonstrated by the conversion of a solid-state laser (Tovstonog et al. 2008) and almost 10 W were achieved in a SHG experiment using an infrared fiber laser (Samanta et al. 2009).

Erbium doped fiber lasers emit around 1530 nm where the absorption in silicon is expected to be low. Current state of the art erbium fiber systems include a master laser and a fiber amplifier and achieve output powers of 2W and much higher power levels are expected in the near future.

As many different applications drive the laser development worldwide, many laser concepts at different wavelength and power levels are available. Depending on the requirements of third generation gravitational wave detectors one of these designs can be chose as the baseline for the light source. However, there is currently no application which has similar stringent requirements on the temporal and spatial stability as gravitational wave detectors. Hence a specific laser development program for third generation detectors will be required to design and build a reliable laser with sufficiently low free-running noise, an appropriate spatial beam profile and good controllability.

The GEO group is currently working on the development of a 1550nm light source with a power level of 50W.

4.2.6 Laser Stabilization

Power stabilization will probably be the most demanding laser stabilization task in future gravitational wave detectors. Technical power noise on the laser can couple via many paths into the gravitational wave channel: asymmetric arms and radiation pressure noise, deviation from the dark fringe, radiation pressure noise. Advanced LIGO requires a relative intensity noise (RIN) of less than 10^{-9}/rHz in the interferometer input beam. The accurate sensing of the needed 500mW laser power at that location is difficult and the signal is still contaminated by pointing, polarization, and potentially even frequency noise. Ongoing research is needed to understand these couplings and reach the required stabilities. Ongoing research is needed to understand these couplings and reach the required stabilities.

4.2.7 Photodiodes

To get a quantum limited measurement of the power fluctuation of 500mW of light, new photodetectors need to be developed with sufficient power handling capability, spatial uniformity and quantum efficiency. First experiments showed that back- illuminated InGaAs diodes show promising features. However neither the spatial uniformity nor a sufficiently high quantum efficient has been demonstrated so far. Furthermore current power stabilization experiments seem to be limited by 1/f electronic noise in photodiodes. The origin of this noise needs to be better understood and either the noise source has to be reduced or easily applicable selection criteria need to be found to get the best devices from the available vendors.

Further R&D in close collaboration between the material and device experts, electrical engineers and groups that can test the photodiodes is needed.

4.3 Squeezed Light Sources

4.3.1 Squeezed light generation

Second generation gravitational wave detectors will be limited by photon shot noise either in the readout path or by coupling via radiation pressure fluctuations over much of their frequency range. Even though the radiation pressure contribution can be reduced by increasing the mirror mass, there are limits to the mirror mass in future detectors. Hence the sensitivity can only be improved by using non-classical light or quantum non-demolition techniques (see Advanced Configuration Section).

Currently two promising techniques are under investigation to produce squeezed light at audio frequencies: squeezing produced in parametric processes in non-linear optical crystals and ponderomotive squeezing produced in suspended mass systems (see Advanced Configuration Section).

Recently 10 dB of squeezing was produced with crystal systems. Work is required to convert such systems from the laboratory performance to a gravitational wave detector subsystem that can run well-controlled and reliably with a high duty factor. The 10 db squeezing at the photodetection corresponds to a factor of 3.2 improvement in sensitivity. The LIGO facility limit is a factor of 10 below the minimum noise floor predicted for AdvLIGO. Given this and the loss of squeeze when coupled into an interferometer, development must focus on reliable squeezers generating significantly more than 10 dB of squeezing and good coupling to the interferometer. Materials research is identified under Optics. As the amount of squeezing increases, control of the squeeze angle becomes more and more critical, another path for research.

4.3.2 Squeezed light implementation

Squeezed light is fragile, highly susceptible to loss, sensitive to scattered light and control of the squeeze angle. A number of squeezer designs are under development. It is important to test their performance when coupled to a detector or a high sensitivity prototype to demonstrate compatibility and robustness of squeezing in various optical configurations.

5 Advanced Interferometer Configurations

The Advanced Interferometer Configurations Working Group (AIC) has supported the R&D towards Advanced LIGO, and members will continue provide advice and assistance during the project phase. The main effort of the group, however, is now directed at establishing the underpinning technology in preparation for potential upgrades to Advanced LIGO and developing future "3rd generation" detector topologies and techniques.

The activities of the group include theoretical analysis, development and application of numerical simulation tools, and a broad experimental program. The goal is to find interferometer configurations that can offer improved sensitivity.

5.1 Advanced LIGO and possible upgrades

Advanced LIGO employs resonant sideband extraction and "DC-readout" (direct homodyne detection of the gravitational-wave induced sidebands at the output port of the interferometer). The AIC working group has provided input to ISC (interferometer sensing and control subsystem within the project) to guide the development of the necessary sensing techniques. Although much of this work is essentially complete the AIC will continue to explore options for minor changes to or upgrade of the baseline design. Work continues in the following areas:

- testing of the new configuration and its controls at the CIT 40m prototype
- optimization of readout parameters, and analysis of sensing and control in Advanced LIGO, including both length and alignment control
- investigation of alternative and modified sensing schemes for Advanced LIGO.

The focus of this work is the refinement of the sensing and control subsystem for Advanced LIGO at the 40m prototype, with support from other experiments (such as at the National Astronomical Observatory of Japan, or NAOJ), and theoretical backup (LIGO Lab and elsewhere). Results from the prototype will be scaled to predict the behavior expected in Advanced LIGO. This scaling has been and will be done through numerical simulation. The work at the 40m, assisted by members of several LSC groups, has already led to refinement of the sensing and control methods for Advanced LIGO, sufficient to define the baseline ISC design

The Caltech 40m interferometer prototype is a central and necessary part of the Advanced LIGO program to test the ISC all-DOF (degree-of-freedom) readout scheme. A refined readout scheme designed to optimize the performance of Advanced LIGO is due for testing during 2009.

The 40m work has motivated development of time-simulations (validation of the e2e end-to-end simulation program, see also below), and has served as an excellent training ground for several postdocs and students who have gone on to make substantial contributions at the LIGO observatories.

Looking to the near future, a readout system employing squeezed vacuum should allow enhancement of the quantum-noise limited performance of Advanced LIGO and other recycled interferometers, by a factor of at least two in amplitude sensitivity (equivalent to a factor of 4 or more in power). Following benchtop tests (at ANU, MIT and AEI-Hannover) a demonstration was carried out at the 40m giving confidence to proceed to full scale implementations on GEO600 (from 2009) and at LHO (following S6).

5.2 Simulation tools

Simulation tools are required to allow extrapolation of results from prototype experiments (usually limited in size and light power) to full scale detectors. The main simulation objectives relevant to configurations design are:

- modeling non-linear effects, such as the lock acquisition process
- assisting analysis of thermal effects and optical aberrations
- studying control schemes
- studying quantum radiation pressure, optical spring effects, and squeezed light, and their interactions with the LSC loops

This work has been essential for Advanced LIGO and will also be needed to support the design of interferometers beyond Advanced LIGO.

The key simulation tools are:

- e2e – the end-to-end time domain simulation program
- SIS (Static Interferometer Simulation) – the FFT based optical model that allows analysis of the effects of all optical aberrations
- Melody – a MATLAB based optical model mainly for analysis of thermal lens effects
- Finesse – frequency domain simulation to study error signals, transfer functions, and shot noise levels (work underway to include radiation pressure effects)
- Optickle/Looptickle, Finesse – quantum mechanical models of the interferometer, required to investigate non-classical effects, including opto-mechanical coupling, and squeezing and related control design.

The LIGO Lab simulation group developed e2e to support Advanced LIGO design. A prototype simulation of Advanced LIGO has been built which can be used to design the lock acquisition control design. SIS was also developed by the Lab simulation group. The other programs originate at various LSC groups.

5.3 Beyond the Advanced LIGO baseline: quantum techniques

Improving sensitivity beyond the Advanced LIGO baseline goal, whether extending the bandwidth or increasing peak sensitivity, is challenging. Advanced LIGO takes the (Dual) Recycled Fabry-Perot Michelson configuration close to the practical limit of performance with 40 kg masses. Advanced LIGO requires strong thermal compensation, and it is hard to imagine that brute-force methods of reducing loss and increasing power are likely to allow a substantial sensitivity improvement. Thus power-handling sets the practical limit to the performance of conventional configurations. Increasing the mass of the mirrors by a large factor to reduce radiation pressure noise seems equally impractical, especially given the cost and complexity of isolation and suspension systems.

Application of squeezed vacuum can, in a reasonably straightforward way, reduce the quantum noise by a modest factor (up to as much as ~5 in amplitude, 25 in equivalent power), and so for a relatively small investment could allow a performance upgrade in, for example, the shot-noise limited region of the spectrum or could allow a trade for similar performance with much lower light power, relaxing technical requirements. The techniques required are generally well developed, up to the point of practical application on prototypes which is a now a crucial and urgent next step.

The uncertainty principle that limits conventional techniques does not, however, set a hard limit to sensitivity. Improvement can be gained, in principle, by removing radiation pressure effects by non-conventional techniques. These all involve the use of squeezed light, either from an external squeezed vacuum source as already mentioned, or generated within the interferometer as a result of correlations arising from the ponderomotive effect[3]. These techniques can be applied in the existing topology – that based on the recycled Michelson interferometer – but even better performance may be obtained in alternative configurations, such as, for example, the Sagnac interferometer. A particular challenge in this area may arise if, for reasons of minimizing thermal noise, the mirrors must be cooled, as then it will be necessary to moderate the light power within the interferometer while reducing quantum noise.

The search is on for a replacement interferometer topology able to give high sensitivity without requiring considerably higher power. Studies of the energetic quantum limit by the MSU and CIT groups have shown that there should be configurations that can meet this goal, and work is underway at several LSC groups to identify the leading candidates. (See also section 4.3 for discussion of sources of squeezed light.)

It is necessary to pursue theoretical and experimental studies of quantum non demolition topologies, including: Sagnac interferometers, “optical bars” and “optical levers” (techniques that rely on optical rigidity in cavities), and filter cavities and readout schemes for use with squeezing.

The initial focus has been on theoretical modeling, but experimental prototypes are required within the next few years both to demonstrate the principles and to begin to clarify the practical difficulties associated with potential future detectors employing any of these techniques. Prior to the development of a detector beyond Advanced LIGO it will be necessary to carry out intensive experimental work on a prototype and this is an emerging activity within the LSC. Effort in this area has not yet reached a sufficient level to bring forth new designs until long after Advanced LIGO is operational.

A short term goal of the LSC groups should be to develop a baseline “3rd Generation” configuration, aimed at achieving approximately 10 times better performance than (baseline) Advanced LIGO, this would take on a similar role to the early Advanced LIGO strawman designs developed a decade ago. This activity would be complementary to similar work being carried out towards the design of the “Einstein Telescope” in Europe.

---

[3] The term “ponderomotive” was introduced to describe the coupling between the amplitude and phase quadratures of a light field arising due to that field reflecting from a suspended, massive mirror. Radiation pressure moves the mirror so changing the phase of the reflected light. In suitably configured interferometers the correlations so generated alter the form of the uncertainty relation in a favourable way.

5.4 Generic techniques in configurations

There are several generic techniques that underpin development of future interferometers. It is important to keep research plans in these areas open and flexible, as it is not yet clear which areas are going to be fruitful. Any of these may prove useful: for example, should thermal-noise considerations point to the use of silicon substrates, diffractive-optics techniques will be required.

Examples of generic techniques[4] that merit continued investigation include (in no particular order):

- Control of high-power coupled cavity systems, where the optical spring is significant
- New readout (sensing) methods and techniques
- Theoretical models of radiation pressure effects in multiple cavity systems
- Configurations based on diffractive optics
- Configurations employing non-Gaussian beams

One area of rapid development is in the use of diffraction gratings either as beam splitters or as devices to couple light into cavities without the need for it to be transmitted through (imperfect or even opaque) substrates. This may be of key importance to cryogenic interferometers, as absorption of light within mirror substrates could cause the dominant heat load and so set a limit to the cooling.

Although it is enormously challenging to produce grating beam splitters approaching the efficiency (~99.99%) of conventional designs, there has recently been significant progress – an area of development that certainly merits support. Gratings as couplers are at a more advanced stage of development, and bench top and small-scale suspended prototypes of all-reflective cavities suitable for application in gravitational wave interferometers have been demonstrated in LSC groups. Further work is needed to show that full-scale gratings can be made and then deployed in interferometers. Gratings may also be important for upgrades of Advanced LIGO, it may be possible to increase the performance of mode cleaners for high power lasers by using gratings.

There is considerable interest in the suppression of the effects of thermal noise in mirror coatings by optimizing the interferometric sensing through best choice of the beam shape at the mirror. Mesa beams and higher-order Laguerre-Gaussian (LG) beam shapes can offer substantially lower thermal noise, but at a cost of increased complexity in the interferometer. Several areas require development: generation and handling of LG beams, analysis of the effect of LG modes on noise couplings and sensing, and prototype tests of interferometers with LG beams.

The idea of using white light cavities, i.e., cavities containing anomalously dispersive atomic systems to increase bandwidth, remains as a possible, perhaps quite low-cost, means of enhancing the high-frequency performance of Advanced LIGO and following instruments. The challenge is

[4] Note that the development of individual optical components required to enable these techniques are not, in general, considered part of configurations research. Details can be found in the Optics Working Group section of this document.

to find a means of implementing a white light cavity, most likely as an adaptation of the signal recycling mirror, which is compatible with other interferometer systems. This requires theoretical development and, in the relatively near future, a small-scale experimental demonstration.

In summary, while working towards concrete designs for upgrades to Advanced LIGO and for 3rd generation instruments, it is important to keep an open mind regarding the future development of interferometer configurations, and to maintain an appropriate level of support for exploration of techniques that, while not currently mainstream, may contribute significantly in the longer term.

6 Third-Generation GW Detector System Considerations

As noted in the introduction, we plan to start discussion on the approach in the LSC for 3rd generation instruments. The configuration of the third-generation GW detectors, including the optical configuration, overall detector structure (L-shape vs. triangular configuration), mirror separation, suspension design etc, will be a function of both the science targets and of the properties of different noise sources. At high frequencies (above ~10 Hz), strain sensitivity improvements are achieved by increasing the light power in the arms or use of prepared light, so the detector configuration will be driven by this requirement. However, at low frequencies (below 10 Hz), the situation is more complex and the configuration will depend on the R&D involving several noise sources. We list some of the questions/issues – some mentioned in diverse places in this White Paper, others unique to the system questions – that will drive the configuration of the low-frequency third-generation GW detectors.

1. Can a surface-based detector deliver the next increment in improved sensitivity? This will depend on the studies of the seismic and atmospheric Newtonian noise. Are there future upgrade paths for the LIGO infrastructure in this epoch – e.g., 'high frequency' detectors?

2. Studies of Newtonian noise, especially underground, may reveal that there are optimal arm lengths and orientations. For example, it may be advantageous to choose the arm length that maximizes Newtonian noise correlations between the corner and end stations, thereby minimizing the Newtonian noise for the overall detector.

3. Suppression of radiation pressure noise below 10 Hz will require further studies of this noise source, and potential new prototypes. Different proposed configurations should be investigated.

4. Cryogenic techniques have been proposed as one way of reducing the thermal noise. Such techniques may have implications on the mirror mass and laser power, thereby affecting the overall detector configuration. A possible alternative is to use all-reflective optical configurations, and/or those which eliminate a sensitivity to mirror motion, which may avoid the need for cryogenic technique. Detailed studies in this field are needed.

5. Alternative suspension techniques may be advantageous at frequencies below 10 Hz (note that simply scaling the pendulum suspensions would lead to extremely long pendulums). Magnetic or electric levitation techniques may become useful, potentially impacting the overall detector configuration.

6. Study non-monolithic proof masses to increase the mass and the angular moment of inertia beyond current and future manufacturing techniques for monolithic substrates. Such proof masses could also have increased surface to volume ratios to support radiative cooling of the optics and lever arms to support auxiliary interferometers for lock acquisition and alignment. However, the influence of the boundaries between the various pieces forming the final proof mass on thermal noise and parametric instabilities has to be studied before such a concept could be realized.

7. The triangular configuration (as suggested by Ruediger) would provide sensitivity to both polarizations. Such a configuration may also have practical advantages, such as simplifying the

escape route design for underground tunnels. Studies of the radiation pressure and thermal noise in this configuration may also impact the detector design.

The above list is certainly not exhaustive, but it indicates the scope of R&D activities that are required to arrive at a configuration design for a third-generation detector. Given the long lead-times for GW detector development, this is the right time to start such R&D studies and to give attention to the broad system questions required to establish a baseline third generation detector design for iteration.