**LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY**

*LIGO Scientific Collaboration*

LIGO-T070137-05-R 6 Sep 2007

# LSC Instrument Science White Paper
# 2007

LSC Advanced Detector Committee, for the LSC

Distribution of this document:
LSC

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 ........ 3**

**2 SUSPENSIONS AND ISOLATION ........ 3**

2.1 INTRODUCTION ........ 3
2.2 R&D TO SUPPORT ADVANCED LIGO COMMISSIONING AND ENHANCEMENTS ........ 5
*2.2.1 Isolation systems ........ 5*
*2.2.2 Suspensions ........ 6*
2.3 R&D TOWARDS THIRD GENERATION DETECTORS ........ 7
*2.3.1 Isolation systems ........ 8*
*2.3.2 Suspensions ........ 8*

**3 OPTICS WORKING GROUP – LSC RESEARCH WHITE PAPER ........ 11**

3.1 RESEARCH ON IMPROVING ADVANCED LIGO OPTICAL PERFORMANCE ........ 11
*3.1.1 Optical coating research ........ 11*
*3.1.2 Fused silica test mass research ........ 13*
*3.1.3 Thermal compensation research ........ 13*
*3.1.4 High power effects in Advanced LIGO ........ 13*
*3.1.5 Modeling thermal effects in Advanced LIGO ........ 14*
*3.1.6 Diagnostics for Advanced LIGO optics ........ 14*
*3.1.7 High power optical components ........ 15*
*3.1.8 Charging of test masses ........ 15*
*3.1.9 Variable reflectivity signal recycling mirror ........ 16*
*3.1.10 Investigation into sources of non-Gaussian noise ........ 16*
3.2 OPTICS RESEARCH AND DEVELOPMENT FOR THIRD GENERATION DETECTORS ........ 16
*3.2.1 Mesa beam optics ........ 17*
*3.2.2 Development and characterization of novel optical substrate materials ........ 17*
*3.2.3 High efficiency grating development and characterization ........ 18*
*3.2.4 Low loss nonlinear optical materials for squeezed light interferometry ........ 18*
*3.2.5 Composite masses ........ 18*
*3.2.6 Coating-less or -reduced optics ........ 19*

**4 LASERS ........ 20**

4.1 ADVANCED LIGO PRE-STABILIZED LASER - BACKGROUND ........ 20
4.2 THIRD GENERATION PSL ........ 20
*4.2.1 High power concepts – Yb:YAG ........ 21*
*4.2.2 High power concepts – slabs, rods ........ 21*
*4.2.3 High power concepts – amplifiers ........ 22*
*4.2.4 High power concepts – adaptive optics ........ 23*
*4.2.5 High power concepts – pump-fibre combiner ........ 23*
*4.2.6 Squeezed light sources ........ 23*
*4.2.7 Laser Stabilization ........ 23*
*4.2.8 Photodiodes ........ 24*

**5 ADVANCED INTERFEROMETER CONFIGURATIONS ........ 25**

5.1 ADVANCED LIGO AND POSSIBLE ENHANCEMENTS ........ 25
5.2 SIMULATION ........ 26
5.3 GENERIC TECHNIQUES IN CONFIGURATIONS ........ 27

# 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 for future gravitational wave detectors, advanced high power laser concepts and prototyping for future detectors, test mass mirror and ancillary optical materials and components, and methods for improving the vibration isolation of test mass mirrors through suspension and seismic isolation. 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 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.

Broadly speaking, instrument science research efforts break down into two categories. Near term efforts in each of the WGs are directed toward improving those aspects of Advanced LIGO which are not yet fully specified or fully understood. The time scale for research projects in this class is anticipated to be over the next three to five years. Longer term research (beyond the five year horizon) is also supported which can be applied to Advanced LIGO as possible upgrades and/or which will inform the design of possible third generation interferometers that are currently being contemplated, such as the European design study for the Einstein Gravitational Wave Telescope (ET).[1] We also note that longer term third generation research can play a role in mitigating unforeseen problems in Advanced LIGO, as our experience with initial LIGO has shown us.

This white paper represents the current thinking of the LSC technical working groups as of mid 2007. It will undergo revisions periodically as we reassess the needs of LSC instrument science.

# 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

---

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

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 ribbons to reduce suspension thermal noise. Prior to Advanced LIGO there will be a set of upgrades, known as Enhanced LIGO, as part of which an Advanced LIGO HAM Internal Seismic Isolation System (ISI) will be installed in each observatory to support the new 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 will reduce risk in the Advanced LIGO project. In addition the testing of the OMC suspension will give some useful experience of a multiple suspension system prior to the installation and commissioning of the other more complicated triple and quadruple suspension systems in Advanced LIGO.

A considerable amount of research and development was also recently carried out on an alternative approach to isolation for the HAM chambers using very low frequency passive isolation, the HAM-SAS (HAM Seismic Attenuation System). However the decision was taken to remain with the baseline active isolation system for Enhanced and 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. However we are now moving into a period of enhanced focus on conceptual designs and laboratory research for future, more advanced detectors so that we can begin to develop the technology to be able to make further advances in sensitivity. The technology development toward 3rd generation detectors is discussed in section 3.

## 2.2 R&D to support Advanced LIGO commissioning and enhancements

### 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 expected to be replicated at LHO during 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 baseline 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 are currently under fabrication and are going to be commissioned at the observatories as part of Enhanced LIGO (as described above). A third HAM ISI system will also be built and delivered to LASTI 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 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. It is also important to investigate other types of sensors, such as laser-ring-gyros like the 'Geosensor' under development by Ulrich Schreiber, 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 interferometry

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', i.e. an interferometric sensor which operates between the point which suspends the mirrors. The system we are developing 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 suspension systems 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 relatively easily, because the seismic tables will not be changed in any way.

### 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 contain excess noise, possibly from clamps or due to stick-slip effects at the break-offs, and that this suspension thermal noise could make a significant contribution to the excess noise seen in initial LIGO. Investigations are thus currently ongoing on alternative wire clamping methods and different metal suspensions in order to better understand and reduce this noise. If feasible, an alternative suspension may be implemented in an intermediate upgrade to LIGO. The work is also directly relevant to the design of the suspensions in Advanced LIGO for those optics whose noise requirements do not require the use of fused silica suspensions.

#### 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 an upgraded version of the triple pendulum suspensions developed for GEO 600. The suspensions for the most sensitive mirrors (those hanging in the BSC chambers) will be built in the UK by a team supported by STFC (formerly PPARC) 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 will be carried out over the next year, with assembly, installation and operational checks plus development of novel control strategies for local and global control.

#### 2.2.2.3 Development of monolithic final stage

Characterization (strength, dimensions, mechanical loss) of fused silica ribbons and 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. Assembly and testing of a full monolithic suspension as part of the quad noise prototype discussed above will take place later this year.

Further research and development of silica ribbon suspensions to increase the dilution factor and hence reduce suspension thermal noise may be investigated as a possible future enhancement to Advanced LIGO. This might be done using a combination of more extreme aspect ratio and higher breaking stress.

#### 2.2.2.4 Violin mode damping

The silica ribbon suspensions will have very high Q violin modes (of order 10^8). Such high Qs 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 build 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.

#### 2.2.2.5 Creep noise

Short, detectable gravitational waves are expected to be rare events in an extremely large body of data, and so characterization and reduction of "background" transients of technical origin is important. For Advanced LIGO, transients originating in the fused silica fibres themselves have been investigated but transients coming from higher up the suspensions and/or from the silicate bonded test-mass "ears" could also contribute. Initial investigations will focus on the level and distribution of non-Gaussian events for wire suspensions as a function of amplitude. Further work is proposed on a full Advanced LIGO suspension possibly using the violin-mode monitors (see 2.2.2.4) at LASTI.

#### 2.2.2.6 Time domain modeling of suspensions

Time domain simulations of the Advanced LIGO Input Optic (IO) subsystem integrating seismic isolation and suspension models developed by SEI and SUS groups are being used to assess its performance and study various physics aspects. These include radiation pressure effects on the mode cleaner's dynamics, frequency and pointing noise due to length and angular fluctuations, and high power related issues associated with the optical power upgrade from 6 W to 180 W.

### 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

Strawman designs for future interferometric detectors have taken baselines of increased test mass size to reduce the effects of radiation pressure (~100 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 Isolation systems

#### 2.3.1.1 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, and the enhanced finesse of the arm cavities. Studies of ways to extract more and better information to move the detector to 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 sensing and control of the relative motion of the optics, even when the main gravitational wave interferometer is not running. We will be studying additional ways of getting information about the state of the detector. 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 suspension systems that employ reflective optics, suspensions that need to dissipate more power, etc.

#### 2.3.1.2 Newtonian coupling

A scientific case may be made to extend the ground-based detector responses to still lower frequencies, perhaps to 1 Hz or lower, to partially cover the expected band gap between Advanced LIGO and LISA. 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 ground, sometimes called the 'gravity gradient' or 'Newtonian Background' noise. There are a number of techniques, some just suggested and some under development, to address this. These include putting the detectors underground or in mines, and/or measuring the local ground disturbances with an array of sensors, and developing a computer model which allows us to predict the gravitational coupling of the environment to the test mass. By 'training' the model with data from the array and the detector, it may be possible to subtract a fraction of the Newtonian Background noise from the gravitational wave signal channel in post-processing.

### 2.3.2 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, its thermal noise properties, and the geometry and assembly of elements including methods of bonding to test masses are being pursued.

#### 2.3.2.2 Low noise blades

Development of fused silica or silicon blades for improved vertical isolation compatible with lower thermal noise than that obtained with maraging steel blades is an attractive option to explore. Such research could have application as a possible future enhancement to Advanced LIGO.

#### 2.3.2.3 Attachment techniques

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

#### 2.3.2.4 Larger masses

Considerations of how to suspend large (100 kg or more) masses, possibly at cryogenic temperatures, is important. 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).

#### 2.3.2.5 Cryogenics – suspension aspects

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

#### 2.3.2.6 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 in the construction phase 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 in particular subsystems of Advanced LIGO, and longer term research into ways around significant limitations in current 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 of has significantly matured [ref Advanced LIGO Reference Design, LIGO-M060056]. Within the OWG, the most important milestone that has been reached is the selection of *fused silica* as the Advanced LIGO mirror substrate material [ref DS report]. 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 test masses must satisfy a number of performance criteria including low absorption, low scatter, uniformity, low mechanical loss, and low thermorefraction. Of these, mechanical loss, optical absorption, and thermorefraction carry the most risk but also the greatest opportunity to improve sensitivity.

Doping the coating tantala layers with titania has been shown to reduce mechanical loss. Titania with a silica dopant as the high index material also promises to improve Brownian thermal noise. Titania-doped tantala/silica is currently the baseline Advanced LIGO coating with silica-doped titania/silica as the fallback. The use of alternative dopants in tantala and/or different high index materials is being explored. 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.

There is currently little theoretical guidance on what coating materials might have improved thermal noise. There are plans 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.

Since the mechanical loss in the coatings typically scales as the total thickness of the high index 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%. Recently, thermo-optic noise from thermoelastic and thermorefractive effects has been included in this optimization. Coatings based on these optimized designs are being fabricated and measured at the Thermal Noise Interferometer. Such an optimized design is expected to be mature enough for use in Advanced LIGO.

Absorption in the coatings will result in thermal 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 cause noise that is driven by the same (coherent) thermal fluctuations. A value for dn/dT for ion beam deposited tantala is not available in the literature, but recent preliminary results indicate that it is likely to be high enough to be a contributing noise source. Existing data from the Thermal Noise Interferometer 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 Advanced LIGO or potential upgrades.

Concerns with scatter in operating interferometers (including initial LIGO and Virgo) indicate there may be a need to develop coatings with lower scatter. It is still inconclusive if higher than anticipated scatter in initial LIGO is a problem with the coating process, the cleanliness and handling, our expectations for scatter, or some combination. 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. This can also help inform whether improved scatter diagnostics are worthwhile for enhanced LIGO. The possibility exists that coating research may have to focus on improvements in this area depending on results from scatterometer tests.

Caltech's Thermal Noise Interferometer has directly measured coating thermal noise from tantala/silica and titania-doped 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 this research. It will also be valuable to directly measure coating thermal noise (both Brownian and thermo-optic) in the final Advanced LIGO coating (likely thickness optimized titania-doped tantala/silica) before coating and installing the Core Optics. The TNI plans 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 a unique low-displacement-noise suspended mirror testbed in the community, could 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.

### 3.1.2 Fused silica test mass research

The OWG has recommended the use of fused silica as the test mass material substrate which was accepted by the LIGO Lab Directorate. While we feel confident that fused silica will deliver the sensitivity goals of Advanced LIGO, several outstanding issues need to be explored in the areas of thermal noise performance, characterization of absorption homogeneity, and fabrication of 40 kg substrates. It is also possible that improved coatings could make thermal noise from silica substrates a 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 level of 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 absorption induced thermal effects. Both bulk and spatially-resolved compensation will be required. For Advanced LIGO, thermal compensation will be applied to compensator plates located in the recycling cavity.

It is beneficial to keep the optic's temperature more constant in the radial direction, to minimize thermal gradients. 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 thermal compensation requirements 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. Preliminary measurements of the mechanical loss of a thin gold coating by Q measuring are underway, as are tests of the compatibility of UV charge mitigation with gold. 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.

### 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. It has been shown that placing a ring of lossy material around the barrel of the test mass can reduce modal Q's sufficiently to greatly suppress parametric instability without significantly increasing thermal noise. In addition, more exotic methods such as spatially-resolved radiation pressure feedback on the mirror surfaces are being contemplated. Experiments investigating parametric instabilities are underway at the Gingin facility.

### 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 FFT model for investigating how the interferometers will perform when operating at full power.

A new version of an FFT-based program is being developed to simulate the 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 physics 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.

### 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

There are also potential consequences of high optical power for components in the pre-stabilized laser, input optics, and output optics. Thermal lensing can be particularly severe in electro-optic modulators (EOMs) and Faraday isolators (FIs), where severe distortion can occur through the introduction of higher order spatial modes. These components must work reliably at their design specifications despite sustained power levels over long periods of time.

Development efforts are underway to fabricate EOMs and FIs that are immune to thermal lensing and birefringence. In addition, trade studies of traditional optical elements and polarizers operating at high power are underway to select the optimum components for Advanced LIGO. Improvements in power handling capabilities for these components could allow for more design flexibility in upgrades to Advanced LIGO, such as the possibility of using a kW class laser to eliminate the need for power recycling.

### 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 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. 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. Preliminary results indicate that the correlation times depend on the type of silica, but can be very long. Continuing work will focus on examining a variety of silica types, different cleaning and handling methods, 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.

Shining UV light at *in situ* optics is being investigated as a way to mitigate charge buildup. This involves testing UV photodiodes, developing driver electronics, and doing experiments to determine if the UV can cause harm to the optics. Coated optics are subjected to UV light for days to weeks at a time, the re-measured for optical absorption and mechanical loss. Preliminary results on tantala/silica optics indicate that the levels of UV needed for charge mitigation will not harm the optics. Follow-up work is planned using other potential coatings for Advanced LIGO as well as whether different cleaning and handling techniques influence the effect of UV. This work is performed in conjunction with the Suspensions Working Group.

It will 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, can explore the possibility of doing this. But other demands on their time and optimization for noise hunting at higher frequencies than is likely for charge noise may make this approach infeasible. 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 is at low frequency, where charge noise is expected to be highest, and has been used successfully for precision measurement 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.

### 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. 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. 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 hopefully 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 will also be explored as sources of transients. Measuring non-Gaussian noise in a tabletop interferometer will 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 if there are to be future ground-based interferometers, research on their optical components must begin well in advance of system level designs.

### 3.2.1 Mesa beam optics

Mirror thermal noise is one of the fundamental factors limiting the sensitivity of gravitational wave detectors. Flat beam profiles are better suited to average over thermal fluctuations and would allow 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. We are concurrently designing modifications to our existing apparatus which will permit us to study a mesa/Gaussian coupled cavity system. 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.

### 3.2.2 Development and characterization of novel optical substrate 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.

For silicon, efforts have focused on acquiring and fabricating large cylindrical test specimens and investigating their mechanical properties as a function of doping. 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.

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 will be 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.  Finally, Advanced LIGO supports sapphire as a back-up to fused silica if unforeseen difficulties arise.

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.

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 ameliorate the effects of thermal loading of transmissive components if the optical loss is low enough. Understanding the temperature dependence of loss in this case could also be a valuable tool.

Finally, the potential downside of cryogenic mirrors is the strong possibility of contamination. 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 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 already been demonstrated using small area gratings. The challenge will be to scale up the optical aperture to what is required for a large scale 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 diffraction angle 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.

### 3.2.4 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.

### 3.2.5 Composite masses

Increasing the mass of the test masses reduces the standard quantum limit. Beyond a certain size, however, it is impractical to generate monolithic masses. Using large masses made as a composite of multiple, smaller pieces can get around this problem. Thermal noise issues related to mechanical loss from the connections 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. Studies of composite masses for mechanical loss can benefit both applications.

### 3.2.6 Coating-less or coating-reduced optics

There are ideas to get around coating thermal noise using corner reflectors or short Fabry-Perot cavities as end mirrors. Corner reflectors would allow for no coatings to be used and the cavities would allow for much thinner coatings than conventional mirrors. Truly developing these ideas so they can be used in an operating interferometer will require a lot of experimental work. A bench experiment is underway forming a cavity wiuth one corner reflector 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. This work is performed in conjunction with the Advanced Interferometer Configurations Working Group.

# 4 Lasers

## 4.1 Advanced LIGO Pre-Stabilized Laser - Background

The development of the Adv LIGO prestabilized laser system (PSL) is almost 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 stage to produce 180W of output power. An output power of 195W was demonstrated in a linear polarized single-mode, single-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 improve this result and 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 server 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 and will be finished in the middle of 2009. 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 coherences 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 to 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 has to be very broad and versatile.

### 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 novel scheme (Adelaide group) 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.

An 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 quarz rotator is used to image one laser crystal into a second one while rotating tangential polarization directions into radial and vice versa.

Beside of 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. In a three times segmented rod for example 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 the laser media (f.e. Nd:YAG) 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 was 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 the 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 ration 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 GWDs.

### 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 Mexican hat 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. Either concepts like the one developed by Stanford University some years ago which uses a Shack-Hartman Sensor and a deformable mirror or completely new concepts should be developed and tested .

### 4.2.5 High power concepts – pump-fiber combiner

For the delivery of the pump light to the laser head the actual advanced LIGO design uses a bundle of 7 fibers per laser head (4 times 7 for the high power laser). By the use of a fiber combiner where the 7 fibers of the pump diodes are coupled into only one fiber a reduction of the number of transport fibers can be achieved and a currently used fused silica homogenizer is not longer required. This reduces the complexity of the system and increases reliability. Fiber combiners at this power levels are available but have to be tested for long term operation.

### 4.2.6 Squeezed light sources

Second generation gravitational wave detectors will be limited by photon shot noise either in the readout path or by coupling via radiation pressure fluctuations. 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 non-linear parametric processes in crystal and ponderomotive sqeezing produced in suspended mass systems (see Advanced Configuration Section).

Recently 10 dB of squeezing were produced with crystal systems. Work is required to convert such systems from the laboratory performance to a GWD subsystem that can run well controlled and reliable with a high duty factor.

### 4.2.7 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. The undisturbed sensing of the power fluctuations at the relevant points in the interferometer is complicated. To achieve a relative intensity noise (RIN) of less than

1e-9/sqrt(Hz) one needs to detect approximately 500mW of light with a shot noise limited detector. All couplings of pointing fluctuations, polarization fluctuations, frequency fluctuations etc need to be small compared to this level. Ongoing research is needed to understand these couplings and reach the required stabilities.

### 4.2.8 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 at Stanford University showed that back- illuminated InGaAs diodes show promising features. However neither the spatial uniformity nor a sufficiently high quantum efficient was demonstrated so far. Furthermore current power stabilization experiments seem to be limited by 1/f electronic noise in photodiodes. The origin of this noise need to be better understood and either the noise source has to be reduced or easy 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.

# 5 Advanced Interferometer Configurations

The Advanced Interferometer Configurations Working Group 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.

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

## 5.1 Advanced LIGO and possible enhancements

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 complete, or nearly so, the AIC will continue to explore options for minor changes to or enhancement of the baseline design. Work continues in the following areas:

- testing of the new configuration, based mainly on the work at the CIT 40m prototype, including tests of component parts such as DC readout photodiodes
- 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 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 40m is a central and necessary part of the Advanced LIGO program to test the ISC all-DOF readout scheme. One scheme, adequate for Advanced LIGO has been demonstrated, and another which may offer some advantages in terms of operational efficiency, is being set up. The 40m work has motivated a lot of the development of time-simulations (validation of e2e, see also below), and has served as an excellent training ground for a several postdocs and students.

Looking to the 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 about two in amplitude sensitivity (equivalent to as much as a factor of 4 in power). This is under serious investigation including bench-top tests at ANU, MIT and AEI-Hannover and a demonstration at the 40m, which has recently led to the completion of a thesis on the topic (Kaisuke Goda).

## 5.2 Simulation

Simulation objectives relevant to configurations design include:

- Modeling non-linear effects, such as the lock acquisition process
- Assisting analysis of thermal effects and optical aberrations
- Study of control schemes
- Study of quantum radiation pressure, optical spring effects, and squeezed light, including their interaction with the LSC loops.

Together these have allowed more detailed and accurate design of Advanced LIGO than was possible for Initial LIGO. Most of the methods will also be needed to support the design of interferometers beyond Advanced LIGO and so continued development is required.

The key simulation tools are:

- e2e - the end-to-end time domain simulation program
- FFT - 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
- Bench - a sophisticated noise model of the interferometer
- Finesse – frequency domain simulation to study error signals, transfer functions, and shot noise levels.
- Optickle, Finesse, MIT code - quantum mechanical models of the interferometer, required to investigate non-classical effects, including opto-mechanical coupling, and squeezing.

The LIGO Lab simulation group has 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. FFT, also developed by the simulation group, needs a major revision to handle the much more complicated environment. The development of the other programs, and the application of the models to system design will be carried out by several groups within the LSC. This work is generally well-supported.

### *Beyond the Advanced LIGO baseline: quantum techniques*

Improving sensitivity beyond the Advanced LIGO baseline goal, whether extending the bandwitdth or increasing peak sensitivity, is very 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 principle, reduce the quantum noise by a modest factor (of order 2) and so for a relatively small investment could allow a performance upgrade in, for example, the shot-noise limited region of the spectrum. The techniques required are generally well developed, up to the point of practical application on prototypes.

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, other than the use of squeezed vacuum at the output of the interferometer. If, especially, thermal noise considerations require the use of cryogenic techniques, moderating the light energy required will help keep the cooling power required to within practical limits.

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: namely, "optical-bar" and "optical-lever" techniques.

Key topics of research in this area include:

- Further development of squeezed vacuum sources to produce higher levels of squeezing, and their application in configurations employing input and output squeezing.
- Theoretical and experimental studies of the extraction of squeezed vacuum produced by the radiation pressure inside the interferometer
- Design of filter cavities and readout schemes for use with squeezing.
- Development of optical configurations to operate beyond the standard quantum limit, including "intracavity" readout methods in general, "optical-bars" and "optical-levers" in particular. The central focus is on configurations that can achieve good performance with light power no larger than used in Advanced LIGO.
- Investigation of other non-standard approaches to interferometry including, for example, displacement-noise-free configurations.

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, starting in the next few years. Effort in this area is growing, but has not yet reached a sufficient level to bring forth new designs until long after Advanced LIGO is operational.

## 5.3 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 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 based on polarizing optics

Note that the development of individual optical components required to enable these techniques are not, in general, considered part of configurations research.

Most of this work can be regarded as exploratory developments towards potential upgrades and interferometer designs beyond Advanced LIGO.