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Instrument Science White Paper

LIGO Scientific Collaboration

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1 Introduction

The LIGO Scientific Collaboration (LSC) conducts research and development 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.

The research is roughly separated into the following categories and working groups:

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

The intent of this white paper is to provide a synopsis of the current and future R&D directions of the five LSC instrument science working 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 for the current detectors. Another element, of growing importance as we push the envelope of system performance, is the physics of materials and condensed matter systems. As this often requires scientists and skills beyond the existing groups, the Collaboration must expand these efforts in order to succeed in the larger goal of gravitational wave astrophysics. Finally, much of the ongoing and planned research commands interest in and of itself; adaptive optics, precision measurement, and quantum interactions with matter are both integral elements of gravitational wave detectors and exciting areas of physics.

Current instrument science research efforts focus on three related projects with three distinct time scales:

- **Incremental improvements to Advanced LIGO.** These are specific, small scale targets of opportunity that promise sensitivity improvements for astrophysical sources. As our experience with Initial and Enhanced LIGO demonstrate, These activities will almost certainly play a role in mitigating unforeseen problems in Advanced LIGO. The results of this ongoing research and development will be incorporated into the current observatories as-needed from now through the era of commissioning and first detections around 2016.

- **Upgrades of Advanced LIGO.** These efforts focus on incorporating Third Generation (3G) technologies into the existing observatories. The most likely upgrade path consists of incremental installation and upgrade phases followed by a science run. In this way there will be a continuous transition from the baseline Advanced LIGO configuration to the 3G LIGO detectors. Included in this scope are things such as (but not limited to) squeezed light injection, squeezing filter cavities, novel mirror coatings, new mirror substrate materials, cryogenic suspensions and optics, and heavy, composite test masses. These upgrades will be installed when Advanced LIGO has made the first detections and completed its science runs, sometime after 2016.

- **Development of a Fourth Generation detector.** On a longer horizon, there is a strong scientific motivation to build a substantially improved instrument in the same spirit as the European Einstein Telescope (ET). We refer to this future instrument as a Fourth Generation (4G) detector. The design for such a detector may include new sites/facilites, underground infrastructure, longer beamtubes, and substantially heavier test masses. The timescale for the implementation of such a detector is ∼2030.

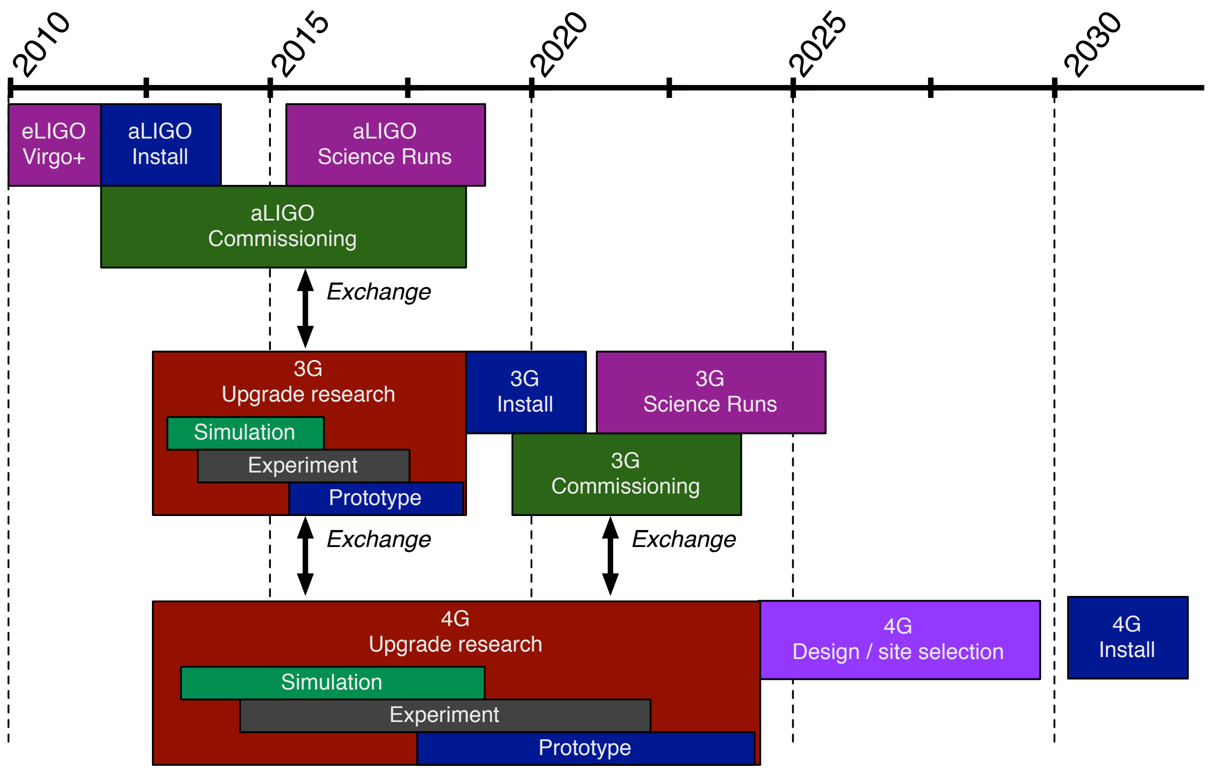

Figure 1: Timeline for 2G, 3G, and 4G gravitational wave detectors.

Figure 1 presents a timeline for these efforts. Although the activities have different time scales, there is a vital and necessary exchange of knowledge, technology and personnel during every stage. As with Initial and Enhanced LIGO, the success of the aLIGO and 3G programs depends on the input from a robust next-generation research program, and vice-versa. This white paper represents the current thinking of the LSC technical working groups as of mid 2011. It will undergo revisions periodically as we reassess the needs of LSC instrument science.

2 Constraints

In this section, we outline a program that identifies the constraints applicable to the 3G and 4G detectors. Appendix D summarizes the current status of Advanced LIGO. Figure 2 presents our current best understanding of the noise sources that will limit Advanced LIGO in the high power, broadband tuning configuration. The sensitivity is determined by shot noise at high frequencies, by mirror thermal noise in the middle frequencies, and by a combination of thermal, seismic and quantum radiation pressure noises at low frequencies.

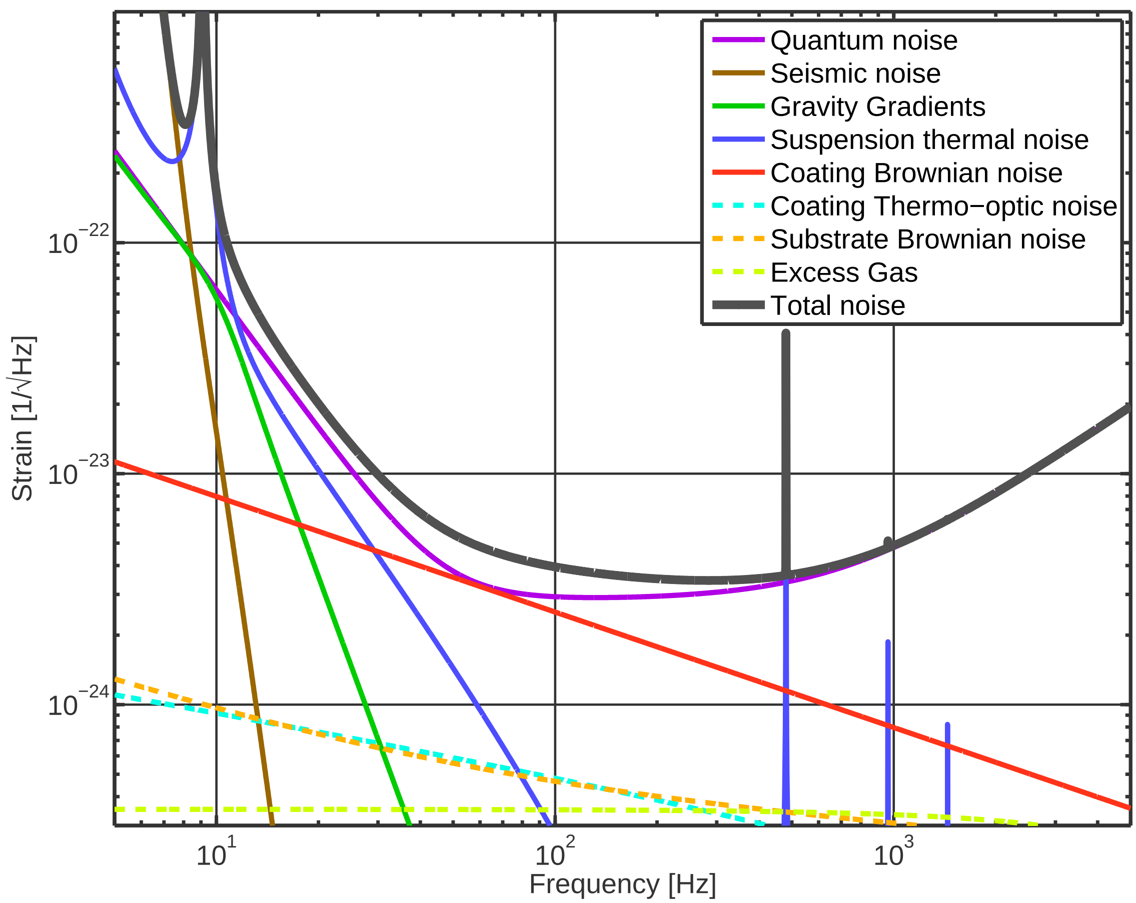

Figure 2: Baseline aLIGO Noise Budget (GWINC v2.0). 125 W input power; broadband RSE tuning.

The 3G and 4G detectors will study novel astrophysics and gravitational phenomena employing technology beyond the current state of the art. The predicted gravitational wave sources emit in a variety frequency bands with a variety of durations, which places a corresponding requirement on the detector sensitivity. Ideally, the design of the 3G and 4G detectors will match the gravitational wave sources and the noise performance will be optimized accordingly. The required sensitivity then dictates the detector technology and design. This design methodology is illustrated schematically in Figure 3. This methodology fails in the current situation without gravitational wave detection – the input astrophysics remains speculative. In the following discussion, the process is reversed. A straw man detector design based on reasonable extensions of current technology is used to calculate the dominant detector noise terms. The resulting instrument sensitivity is then used to evaluate the accessible astrophysics, which in turn influences the instrument design.

In the following discussion, the proposed technologies are used in the straw man design to establish concrete noise estimates. Other technologies and designs may achieve comparable sensitivity and should be investigated.

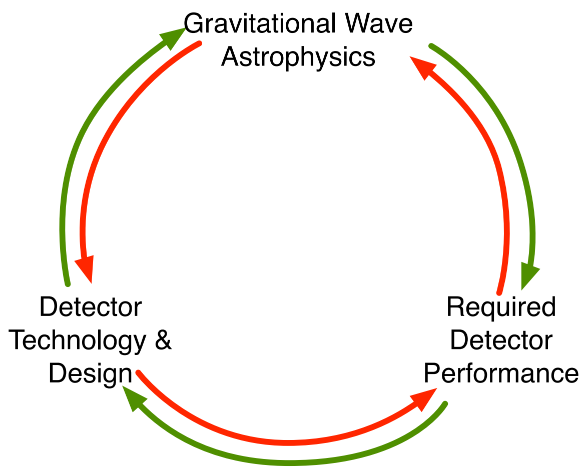

Figure 3: The interplay between astrophysics, sensitivity, and technology in detector design.

2.1 LIGO 3G

The LIGO 3G upgrades must be ready for installation after aLIGO, by $\sim$ 2018; to contribute to risk mitigation in aLIGO, 3G technologies must be ready by $\sim$ 2016. To bring new technologies to the required maturity, we must begin laboratory scale R&D by 2012. Of course, its difficult to know exactly what upgrades will be most beneficial before detection with Advanced LIGO. Lacking this knowledge, we instead choose to develop those technologies that will produce a significant improvement in the predicted limiting noise sources and thereby a broadband sensitivity improvements.

The target 3G noise spectrum is shown in Figure 4. The optimization which lead to this strawman configuration is described in Section 3.1. The elements considered for this design are:

1. Coating and suspension thermal noise are the aLIGO limiting noise terms in the 5 – 50 Hz range. To improve the overall detector sensitivity, these noise terms must be improved by a substantial factor. For the purposes of our 3G design we assume a 2.5x reduction in noise (amplitude). This improvement requires a directed research program for improvements in the test mass coating technology (e.g. materials) Details can be found in Section 5.

2. No major changes in the facility, nor significant modifications to the mirror size. We rule out cryogenic mirrors in this time frame.

3. For the suspension thermal noise, we assume that the bounce mode frequency is lowered by a factor of 3 with a concomitant reduction in the vertical mode thermal noise (see Section 6.2). Also a factor of 3-5 reduction in the pendulum mode thermal noise, either through modifications of the room temperature silica suspensions or through the use of cryogenic suspensions.

4. Newtonian noise mitigation through active noise cancellation to be developed during the 3G time scale. We assume a reduction by a factor of 10 of the Newtonian noise relative to current predictions (see Section 6.2.3).

5. There are optical configurations allowing the injection of squeezing, which may be filtered by cavities with moderate lengths (10's of meters), or the full 4 km arm length. (See Sec. 4.1.1.

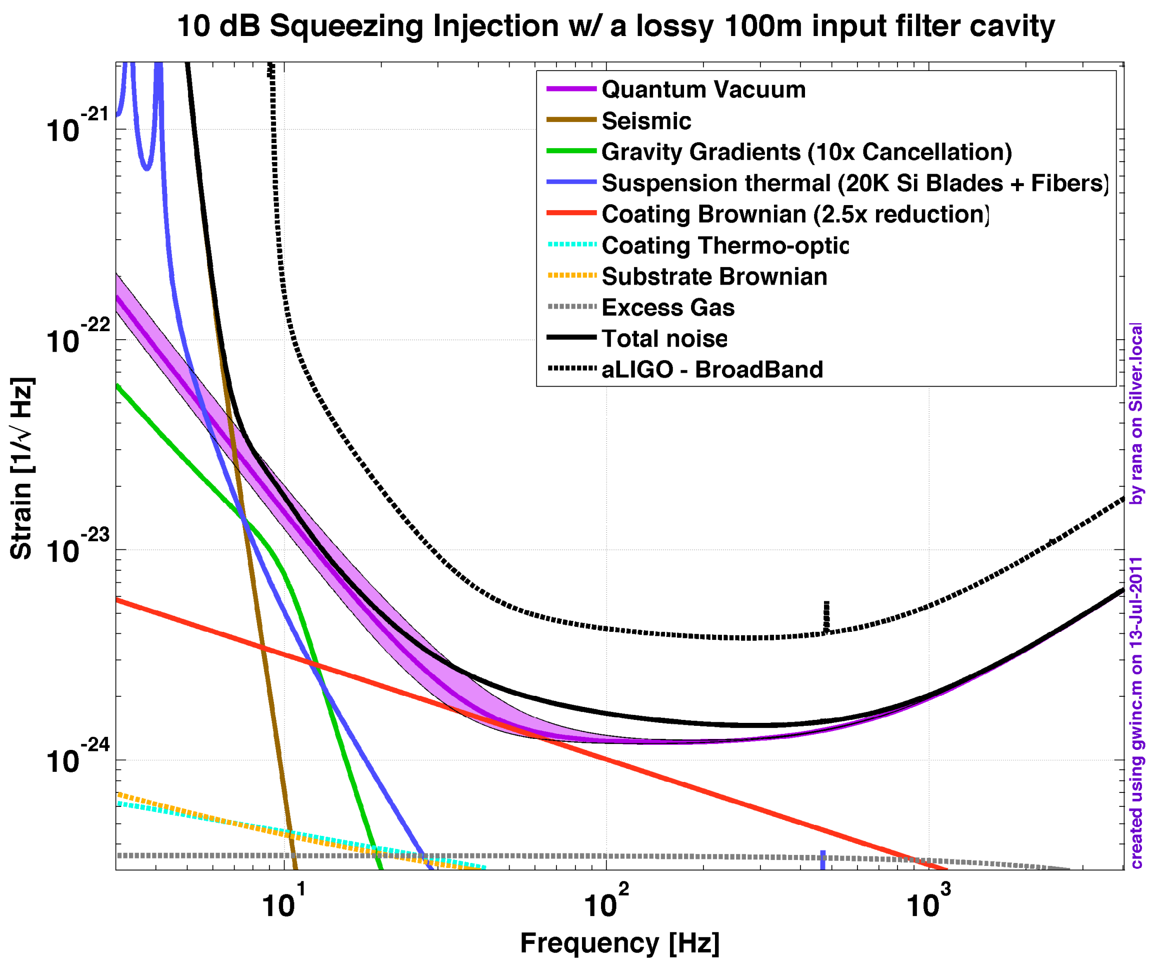

Figure 4: Noise spectrum using 10 dB of squeezing injection and a 100 m squeezing filter cavity.

The straw man target 3G noise curve, shown in Figure 4 improves the sensitivity by roughly a factor of 3 relative to aLIGO and lowers the low frequency cutoff to 5 Hz. Simulation and modeling of the 3G detectors should be completed within a few years, and should pay special attention to practical imperfections, and sensing/control issues.

2.2 LIGO 4G

The LIGO 4G detectors will be designed to study the specific astrophysical sources that have been observed by 3G detectors. Thus the bandwidth, configuration, and required sensitivity of the 4G detectors remain uncertain. For LIGO 4G, the constraints are less concrete than 3G, yet they allow more dramatic improvement of sensitivity.

Although the 4G target sensitivity remains uncertain, the current limitations are well known.

Here we list several areas of current and planned research and development targeting the next generation interferometers:

- *Novel system configuration* including a. multiple co-located interferometers; b. additional detectors in South America, Asia, and Australia; c. coherent interferometer arrays and d. underground sites.
- *Extended low frequency sensitivity* by employing a. Newtonian noise prediction and subtraction; b. atomic inertial sensors for low frequency tilt and seismic sensing; c. femtometer scale displacement sensors; d. extremely low noise sites; and e. Quantum Speedmeters.
- *Improved suspension thermal noise* through a variety of mechanisms including a. massive, composite test masses; b. magnetic and magnetic assisted suspensions; c. novel suspension materials; and d. cryogenic suspension elements.
- *Improved mirror thermal noise* by a combination of techniques including a. large diameter beams and adaptive optics; b. crystalline substrates and coatings; c. grating based optics and d. cryogenic mirrors.
- *Novel quantum-mechanical readout systems* to exploit the interaction of the test masses with the quantum laser field using a. optical bar detectors; b. dynamic signal recycling; c. wide bandwidth white-light cavities; and d. ponderomotive squeezing.

These elements form the basis of the still-nascent LIGO 4G program. The gravitational waves discovered in the first detections will dictate many of the 4G design decisions. However, the technologies described above will require many years to reach maturity with the LSC member groups leading the research effort.

3 Advanced Interferometer Configurations

The AIC group has two chief purposes:

- Coordinate the integration of interferometers systems and make trade-offs between components to optimize the sensitivity.
- Design the sensing and feedback control for the interferometer length, alignment, and wavefront (thermal compensation) systems.

3.1 Configurations

With the other noise sources,reduced by using techniques introduced in Section 2.1, the quantum noise will become the dominant noise source over the band from 10 Hz to 10 kHz. To decrease the quantum noise, we need to manipulate the coherence of light at the quantum level; there are several proposed techniques, as detailed in Section 4.

In order to converge on a configuration target for the upgrade to Advanced LIGO (a.k.a. LIGO 3G), we have used a modification of the GWINC code (GWINCdev) to explore the sensitivity curves from these listed configurations. We have compared them systematically in terms of experimental complexity—number of additional large optical components—and gain in sensitivity—broadband improvement compared with Advanced LIGO.

Through the optimization (Sec. 4.1.8), we found that the net gain in sensitivity (after including other technical noises) only differs slightly among different configurations due to the low-frequency technical-noise barrier. However, their complexity varies a lot—some require only a few additional optical components while some require many. The least complicated one is the squeezed light injection with a short filter cavity. It is, therefore, an experimentally feasible candidate for upgrading Advanced LIGO in the intermediate stage. The strawman plot of its sensitivity is shown in Figure 4. It assumes 10 dB squeezed light injection (with 5% loss) and a 100 m filter cavity. The shaded area shows the effect of optical loss in the filter cavity (from 30 ppm to 100 ppm round-trip loss) on the sensitivity. The filter cavity rotates the squeeze angle in an optimal way, and this allows for a factor of $\sim$3 reduction of both low-frequency radiation pressure noise and the high-frequency shot noise; thus gives a broadband sensitivity enhancement.

For the 4G detectors, a similar procedure could be used but a with more drastic assumptions for improvement of each subsystems. Since we may employ several types of interferometers at a single site (or multiple sites) which compose a xylophone array, the opimization process should include different types of criteria.

3.2 Interferometer Sensing and Control

The Interferometer Sensing and Control (ISC) consists of three areas (LSC, ASC, and TCS). In addition to those, general remarks about the control systems and the interferometer simulations are made in the AIC context.

The following is the overview of the three subsystems:

Length Sensing and Control (LSC): The LSC manages the interference conditions of the fundamental mode in the interferometer in order to maintain a high sensitivity to GWs. The longitudinal distances between the mirrors are adjusted so that they fulfill particular inteference conditions.

Alignment Sensing and Control (ASC): The ASC primarily controls the 1st-order optical modes in the interferometer by adjusting the angular direction of the mirrors. In addition to the LSC, this system is also necessary to keep the high sensitivity of the interferometer. Although the angular motion of the mirrors are locally stabilized by the vibration isolation and the suspension systems, the global control is necessary in order to realize the stable interferometer operation.

Thermal Compensation System (TCS): The TCS control the higher-order modes in the interferometer. The importance of the TCS has been increasing from the experiences on the first generation detectors and their enhancements. The sensing of the thermal aberration is discussed below while the TCS actuators are described in Section 7.3.

3.2.1 Length Sensing and Control

The Advanced LIGO interferometers consist of five coupled cavities that must resonate simultaneously to reach the operating point. The LSC receives the length sensing signals from the photodiodes and sends them to the actuators on the suspensions so that those five degrees of freedom stay at the operating point. Between the sensing and the actuation, the signals are processed by servo filters so that stable feedback control of each loop is established.

The aLIGO LSC employs a combination of RF heterodyne detection and DC readout. This RF sensing scheme comprises the Pound-Drever-Hall technique, Schnupp modulation, and third harmonic demodulation technique as a baseline design. The DC readout scheme provides sensing of the GW signals with a better shot noise limit than that of the RF detection and more immunity to the laser noise couplings when combined with an Output Mode Cleaner (OMC). Those techniques have independently demonstrated by the Enhanced LIGO and GEO600 interferometers, and other prototype interferometers. Therefore the task for the aLIGO interferometers is to integrate these techniques and find any hidden issues to slow down the actual commissioning. This is also the role of the Caltech 40m prototype.

Detuning of the signal recycling cavity is also a part of the design. This detuning improves the sensitivity of the device for neutron star mergers by lowering the noise level at around 200 Hz where the quantum noise is the dominant noise source of the tuned-recycling case. However, the previous experiences at GEO600 and Caltech 40 m show the presence of obstacles to be overcome in lock acquisition and noise couplings. Although the first phase of aLIGO will use the broadband signal extraction, the issues of the detuning should be revisited with simulations and the prototype experiments.

The LSC system for 3G/4G detectors will likely also follow the above technologies. Details of the system, however, will greatly depends on the optical configuration to be deployed as the future detectors may face with further complication with more mirrors and cavities . Once the optical configuration is set, the detailed analysis of the LSC plan should follow. In addition to the techniques already used in aLIGO, new complications may require new techniques such as multiple carriers and/or multiple lasers with single or multiple wavelengths.

Especially for the 4th generation detectors, the Suspension Point Interferometer could be a practical solution to mitigate the vibrational noise caused by the heat link of the cryogenic cooling system.

Lock acquisition The new feature of the aLIGO LSC is employment of the Arm Length Stabilization (ALS) system. This system enable us to lock the long arm cavities in a deterministic way with the guidance of auxiliary beams injected from the end mirrors.

Advanced LIGO will achieve lock using two single arm interferometers to control the arm cavity mirrors independently of the Michelson and signal recycling cavities. The arm cavity locking requires stable frequency-doubled lasers at each end station, with each laser frequency referenced to the master laser in the vertex, 4 km distant. For Advanced LIGO, these lasers are stabilized after first locking the arm cavities. For higher finesse cavities in LIGO 3G and 4G, there may be a need for an improved laser stability. Research into stabilized lasers using length controlled fibers, isolated reference cavities, and atomic frequency references may all address this need.

In addition to stable lasers, the more complex LIGO 3G interferometers may require additional lock acquisition techniques. Low noise phase meters similar to the LISA phase meter provide an option for determining the relative position of all the interferometer optics simultaneously. This includes the possible use of the pseudo random phase modulation for digital interferometry. Although these phase meter techniques require an order-of-magnitude improvement over current sensitivities, a phase meter lock acquisition system could be deployed on Advanced LIGO and provide substantial risk mitigation.

High power photodetection Unlike previous generations of interferometers, the Advanced LIGO, 3G, and 4G interferometers will detect substantial amounts of DC photocurrent at signal frequencies below 10 Hz. In this region, photodiodes are subject to excess 1/f noise that degrades their performance. Research to characterize, understand, and improve upon photodiodes will be necessary to detect the signals from high power interferometers.

In addition to the DC photocurrent, the RF power received by the RF detectors will also increase. Increasing the SNR in the RF detectors will directly reduce the aux. controls noise (a limit in nearly all GW interferometers) and so needs to be explored carefully.

Output Modecleaner and squeezing related topics Injection of squeezed vacuum from the dark port improves the shot noise level of the interferometer. The recent development of GEO600 with the squeezer demonstrated clear improvement of shot noise level by 3.5 dB. Every 3 dB of squeezing is equivalent to a factor of 2 in power. In this sense, the squeezing injection can be considered to be risk mitigation for high power issues.

The trade-off of using squeezing injection is the technical issues involved: Optical losses and scattered light noise.

The optical loss in the squeezer path injects unsqueezed vacuum and limits attainable reduction of shot noise. For example, a loss of 25% limits the reduction of the shotnoise level to 6 dB. One of the largest causes of the loss is the Faraday isolator between the squeezer and the main interferometer (see also Section 7.5.2). Also mode-mismatching reduces the shot noise limited performance and linearly degrades squeezing performance. Resolving these issues will open the door for extracting the usefulness from further enhanced squeezing factors.

Scattering between squeezers and the main interferometer is another issue to contaminate the signal of the interferometer. Although insertion of the Faraday Isolator in between naturally reduces the back scattering, it also reduces the transmission efficiency thus limit the ultimate performance of the squeezing injection. In addition to the passive stabilization of the optical paths, development of the active control of the scattering path may be beneficial for the risk mitigation of aLIGO as well as for the future detectors.

Output Mode Cleaner Future interferometers use high finesse mode cleaning cavities to prepare the input laser beam for use in the interferometer and to ensure that the output photodetectors sense only the interferometer's fundamental spatial mode.

The DC sensing noise of the OMC observed in eLIGO is just barely compatible with aLIGO displacement noise. The 1/f behavior of the DC sensing noise starts rolling up from around 40 Hz while fortunately the requirement does so. For future detectors, this will have to be reduce by $\sim$1 order of magnitude.

The mode matching between the interferometer and the OMC is particularly critical for future interferometers as discussed in the previous section. Output mode matching presents a particular difficulty as it varies with the interferometer thermal state. The eLIGO interferometers saw numbers as bad as 85-95%. Current research explores the use of deformable mirrors for adaptive mode matching, together with "Bull's Eye" wavefront sensing for measurement.

3.2.2 Alignment Sensing and Control

DC alignment sensing The alignment sensing and control subsystems simultaneously control two degrees of freedom for each optic in the interferometer. Advanced LIGO will employ DC sensing to detect the arm cavity and recycling cavity positions. Future improvements will be aimed at lowering the 1/f noise in the photodetectors, increasing the number of pixels, and combining position and length sensing in a single photodetector.

RF alignment sensing The Advanced LIGO alignment system relies on radio frequency (RF) quadrant photodetectors and heterodyne detection to create alignment signals. At some readout ports, the photodetectors are constrained by a combination of low light levels, high static RF signals, and small signals. To further complicate matters, the detectors must simultaneously measure multiple RF sidebands. Future research includes Monte-Carlo based RF circuit optimization, direct RF signal subtraction, and multi-pixel sensors with integrated readout chips.

Sidles-Sigg instability It was avoided in Advanced LIGO interferometers to have a severe impact by the angular instability induced from radiation pressure (Sidles-Sigg instability) was avoided. However, this is still a potential threat for the 3G/4G detectors. The investigations to mitigate this instability should be carried out in both of the practical and innovative aspect: reduction of the control noise level of the ASC system and exploration of any new control scheme to resolve the instability issue such as an application of optical trapping technique.

Towards ASC of 3G/4G detectors As the optical system incorporates more components, the Alignement Control System gets increasingly complicated.

Already in Advanced LIGO interferometers, we will be required to develop new techniques to control the alignment of the OMC and the squeezers, in addition to the already-addressed ASC of the main interferometer.

The higher power operation of the interferometer in the future generation detectors will involve coupling of the higher order modes into the field content at the dark port. This coupling will depend on the angular motion of the mirrors and may make the ASC work more complicated. To address the issue, deep investigation of the interferometer behavior with simulation is required before we face the actual issue.

Actually, the control noise of the ASC system has consistently been one of the main limiting noises in the low frequency band for all of the gravitational wave detectors.

We will eventually reach the noise limit of the conventional DC/RF readout schemes to maintain the practical sensitivity of the interferometer. At that point, we will have to develop a novel angular readout system.

3.2.3 Thermal aberration sensing and control

Mitigation It will be necessary to apply thermal compensation methods to stabilize the recycling cavities and maintain the radii of curvature of the test masses against thermoelastic distortion effects resulting from circulating light absorbed in the mirror coatings and substrates and subsequent heating of Advanced LIGO test masses. Both bulk and spatially-resolved compensation will be required. Thermal compensation will be applied to compensation plates located in the recycling cavity, and to the test masses themselves. To minimize the effects of these distortions the optic's temperature must be maintained radially uniform [16].

One method to maintain a uniform temperature profile is by coating the barrel of the optic with a thin layer (a few microns) of a metal with high IR emissivity such as gold. Finite element models indicate this would greatly reduce the radial temperature gradient in Advanced LIGO style test masses. This technique is planned for the Advanced LIGO compensation plates, but it may be possible to expand it to other important optics, possibly including the test masses. Adding a gold barrel coating to the optics has implications for other aspects of the design including thermal noise, charge mitigation, and parametric instabilities [17]. Measurements of the mechanical loss of a thin gold coating indicate that the gold coating can be applied without adversely affecting thermal noise. Gold coatings applied to the barrel for thermal compensation purposes need not reduce the optics modal Q 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 an upgrade to Advanced LIGO.

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 [18]. This will require research on carbon dioxide lasers, to reduce noise and possibly boost power, and potentially on measurement and control issues. Different scanning techniques (galvo mirrors, crossed AOMs) will need to be investigated to develop a system that does not introduce noise into the interferometer. In addition, it might be possible to develop MEMS or other technology based spatial light modulators to allow a programmable heating beam profile.

Local radiant heaters are used in interferometers to provide bulk curvature corrections to mirrors without injecting displacement noise. These must have a uniform heating pattern at the mirror to minimize astigmatism. Future work on radiant heaters will improve the heaters' radiant uniformity and introduce tailored nonuniformities to account for non-axisymmetric features of the interferometer optics. Other future research would make the heaters more physically robust, and minimize their electrostatic interaction with the test masses [19].

Thermal aberrations can be corrected not only by adding heat to the mirror to flatten the heat pattern caused by absorbed interferometer light, but also by directly removing the heat from the absorbed interferometer light itself, through radiative cooling to a nearby cold surface. Such a technique has been proven in principle but not developed into a useful technique for high power interferometry.

Wavefront modeling 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 light propagation, for investigating how the interferometers will perform operating at full power [20]. A new version of the FFT-based SIS program is being developed to simulate the full interferometer. 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 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. In 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 [21].

Wavefront diagnostics 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. For a specific example of this, see T1100250-v2 [22]. 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. On-axis and off-axis Hartmann wavefront sensing have 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 experiments have measured wavefront changes smaller than $\lambda/3000$ [23]. When applied to off-axis tomographic measurements, the current measured accuracy is $\lambda/120$, limited by factors other than the Hartmann sensor itself [24]. Further research is aimed at improving this performance. Avenues for improvement include simple and stable injection schemes for Hartmann probe beams into working interferometers and incoherent probe beam sources with high power and low noise.

Phase Camera In addition to the Hartmann style sensors, it would be useful to use Phase Cameras (essentially multi-pixel RF Wavefront Sensors). These could be used to implement real-time wavefront correction. Primitive phase cameras have been used in iLIGO and iVirgo, but there were problems due to the scanning induced backscatter. Future phase cameras should allow for wavefront sensing of individual sidebands simultaneously without any moving parts.

3.2.4 General Control Issues

Fast data acquisition Currently the data acquisition rate is limited to a sampling rate of typically 16 kHz to 64 kHz. For some specific purposes high speed data acquisition will add convenience for comissioning. In the first phase this can be a ring buffer to store the data for (for example) ∼10 min to catch lock acquisition/lost events or fast transient noise of laser intensity/frequency.

Adaptive Noise Cancellation Adaptive noise cancellation techniques will be widely used in the Advanced LIGO interferometers and the future detectors. Basically, noise cancellation based on Wiener fiters eliminates the noise in a target signal correlated to witness channels.

This family of techniques has a wide are of applications such as seismic noise reduction, Newtonian noise subtraction, and magnetic/acoustic noise cancellation. The coupling of auxilliary LSC degrees of freedom to the main GW signals were the true sensitivity constraint in the initial and Enhanced LIGO interferometers. The noise cancellation technique can also be applied to eliminate this noise.

Up to now, a basic scheme with linear adaptive noise cancellation is being tested on the CDS system at the 40 m prototype. In the future, in addition to the linear noise subtraction, subtraction of bilinear noise should also be investigated as it has many places to be applied.

Automatic Optimization As the interferometer configuration gets complicated, the optimization of the system parameters gets significantly difficult. For example, we have to deal with the different range and frequency dependence of the multiple sensors and actuators at each stage of the suspension and isolation system. The diagonalization of those sensors and actuators will be complicated more than we have ever had. Optimization of the hierarchical control will depend on the noise level of the interferometer and will be time-consuming.

All of the optimization procedures in the future interferometers should be automated within the interferometer control system. This discipline should be enhanced in the future detectors with continuous effort toward automatic comissioning with "machine learning". New involvement and collaboration with researchers of this particular field is encourged.

Virtual Interferometer The flexibility of the Advanced LIGO CDS system allows, for the first time, the beginnings of the "Virtual Interferometer".

Basically, the future detectors should have a computer facility which enables us to login and run the control system for the test of operating and diagnosing tests without having the actual detector equipment. At the beginning this can only be a tool for the comissioning and development, as seen in the "Simulated Plant" concept being tested at the 40m prototype, but eventually can provide various realtime test of the interferometer behavior by cooperative interaction with the other simulation tools. This should include the test of the online data production for mock data challenges.

3.2.5 Simulations

The motivation for the development of interferometer simulations was discussed partially in Section 3.2.3.

The configuration level simulation is discussed in Section 3.1. For the 3G/4G configuratios, an international collaboration should be advised to enrich the options dealt with the configuration optimization so that the experiences of ET consideration will be reflected.

A missing area is the comprehensive mechanical simulation tool for the vibration isolation and suspension design which includes the capability to handle the prediction of thermal noise.

In the AIC context, frequency domain simulations like Optickle, Looptickle, Pickle, etc. should be unified and enhanced to diagnose various noise models. This will provide the quick investigation capability we need during the commissioning.

4 Quantum Noise and Quantum Mechanics

The Quantum Noise Working Group (QNWG) covers research involving theoretical studies of squeezing/QND topologies; development of quantum radiation pressure dominated and QND apparatus; Experiments to prototype QND: filter cavities, variational readout, etc.; and development of squeezed light sources.

4.1 Theoretical studies of squeezing/QND topologies

4.1.1 Optical Filtering and Strategies for Injecting Squeezing

Phase and Amplitude Filters Optical filters have been designed to take advantage of injected squeezing, as well as adapting optimally to ponderomotive squeezing (i.e., squeezing generated internally in the interferometer), and achieving so-called back-action evasion. The use of input squeezing to improve interferometer sensitivity originated from works of Unruh and Caves [32, 33], which considered frequency independent squeezing. The use of optical filters to achieve back-action evasion originated from the variational readout strategy of Vyatchanin et al. in the time domain [34], which considered the varying readout quadrature in time. The filters we discuss here can rotate quadratures according to sideband frequency, and are best adapted for use in LIGO:

- Kimble et al. [35] designed Fabry-Perot cavity filters (with one coupling mirror and perfect end mirrors) for optimal squeezing injection, as well as optimal readout, in broadband Fabry-Perot Michelson interferometers (see Fig. 5 for layout of these configurations, as well as left panel of Fig. 6 for an individual filter). These filters achieve their goals by rotating quadratures in a frequency dependent manner. Kimble et al.'s filter design strategy (including the use of successive Kimble filters) is generalized by Purdue and Chen [27] into general quadrature rotation angles.

- Harms et al. [36], Buonanno and Chen [37], generalized Kimble filters to detuned signal recycling. They obtained the optimal filter for injecting frequency-dependent squeezing and detecting constant homodyne phase. They also obtained the optimal frequency dependence of homodyne detection, but did not describe filters that realize such angles.

- Corbitt et al. designed *amplitude filters* [38], which are made up from impedance-matched cavities: either amplitude or phase squeezing is injected into the interferometer, with a different *portion*, depending on the frequency. (See right panel of Fig. 6.) They also considered serial and parallel amplitude filters.

- Khalili [39] substantially improved the amplitude filter by adding homodyne detection at the open port — and subtracting this channel from the main detection channel with the appropriate gain. (See right panel of Fig. 6.) This was further developed [40].

In idealized situations, input squeezing combined with output filtering can totally eliminate radiation-pressure noise and suppress shot noise by the squeeze factor. Input squeezing combined with input filtering, on the other hand, does not eliminate radiation-pressure noise, but simply suppresses shot noise and radiation-pressure noise by the squeeze factor.

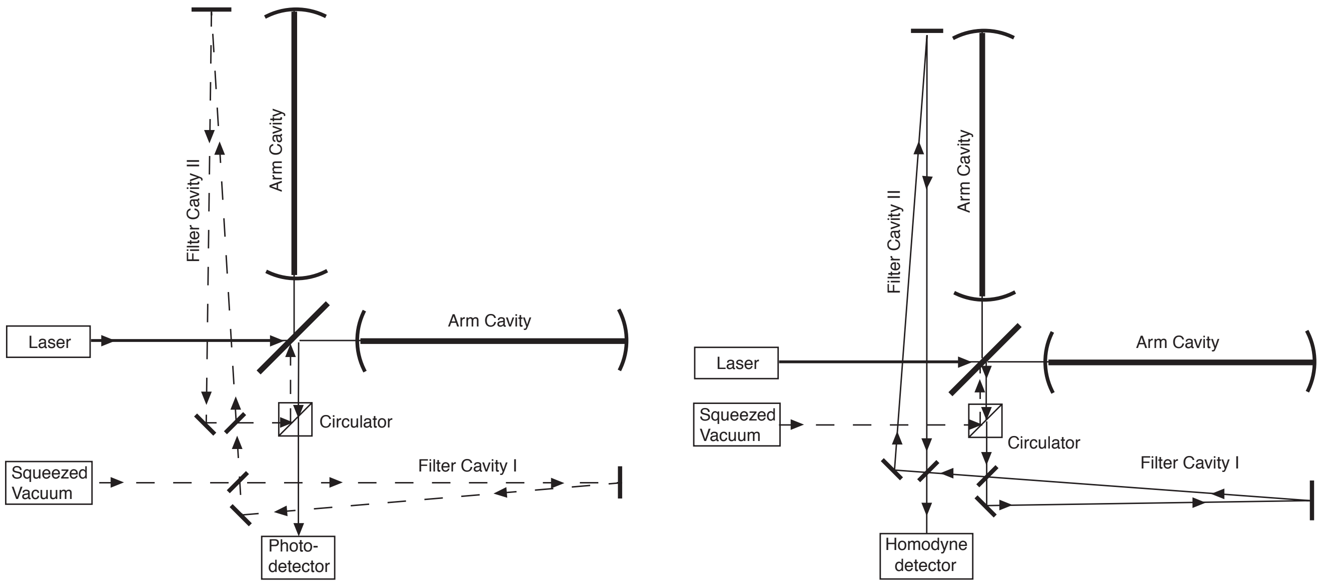

Figure 5: Frequency dependent input squeezing (left panel) and Frequency dependent homodyne detection (right panel) with optical filters. [Adapted from Kimble et al. [35].]

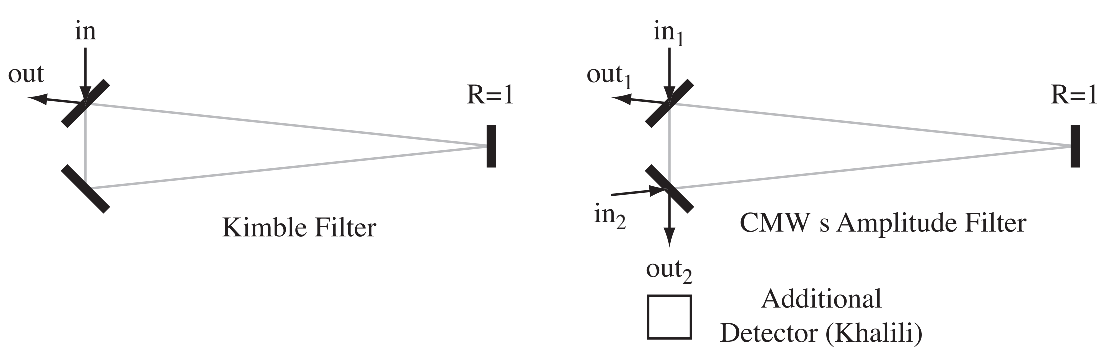

Figure 6: Left Panel: Kimble filters, with only one input and one output. Right Panel: Amplitude Filter proposed by Corbitt Mavalvala and Whitcomb, and improved by Khalili, who proposed adding an additional homodyne detection.

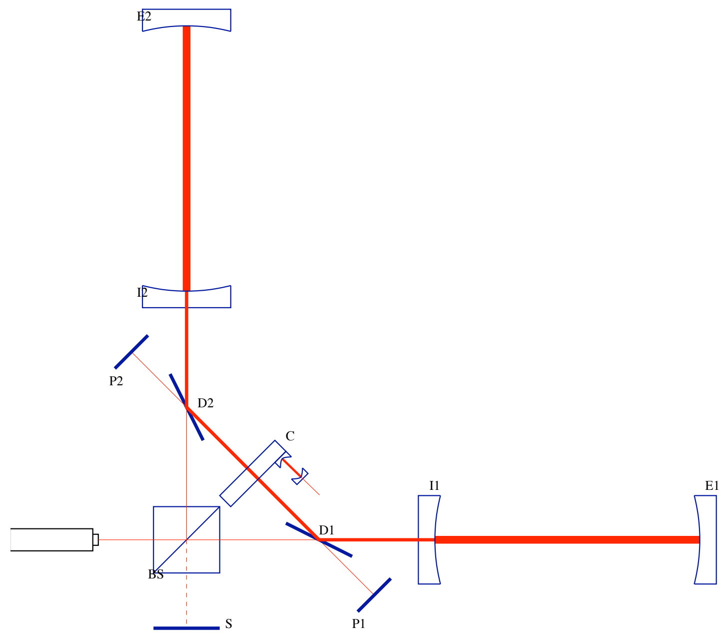

Figure 7: Interferometer with an intracavity readout scheme, taken from Ref. [46]

In contrast, the advantage of output filtering is achieved by utilizing the ponderomotive squeezing generated inside the interferometer, which requires measuring output quadratures with low signal strength. As a consequence, output filtering is more susceptible to optical losses.

4.1.2 Time-dependent Homodyne Detection

In a detuned interferometer, the GW signal appears in both quadratures of the output electric field. The sensitivity of the interferometer can be shaped by measuring a frequency dependent combination of these quadratures (as in GEO600), but also by having the measured quadrature be a *time dependent quantity*. For example, this could be done by varying the phase of the LO field used to do the signal extraction.

4.1.3 Modifications to the Signal Recycling Cavity

Long Signal Recycling Cavity The Advanced LIGO signal cavity is designed to be $\simeq$ 50 m. It may be possible to extend this cavity to 4 km, as shown in Fig. 9. A long signal-recycling cavity has been shown to be advantageous in that it is non-degenerate [1]. In addition, long SR cavities have been shown to offer a signal enhanced and Quantum Non-Demolition configurations.

As shown in Fig. 8, in an interferometer with a tuned long SR cavity modulations to the carrier slosh between the arm cavity and the SR cavity, at a frequency Δ. When the sloshing frequency Δ is much higher than the signal-extraction frequency δ (the rate at which signal leaks out from the interferometer), the situation is described as "double signal recycling", in which both sidebands $\omega_0 \pm \Delta$, instead of a single sideband as in the usual signal-recycling

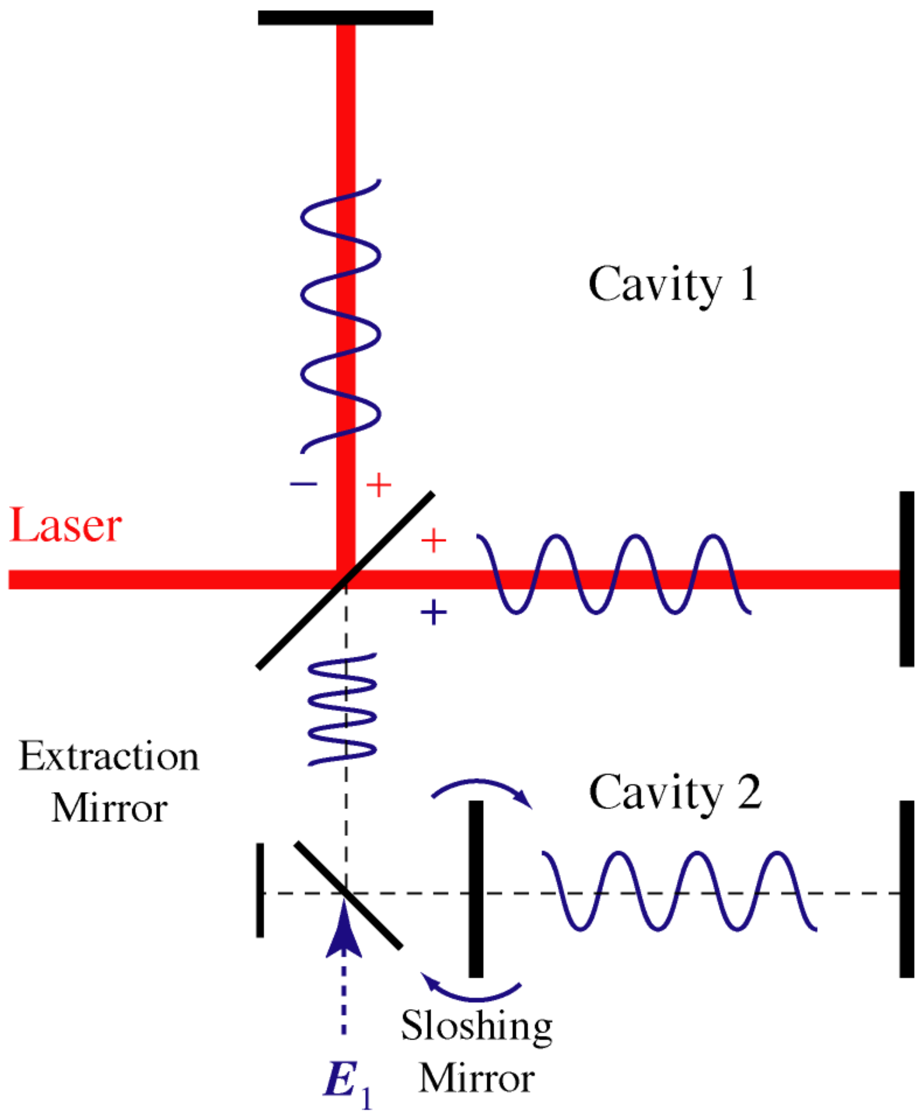

Figure 8: Diagram of a long SRC used as a Sloshing Speed Meter (SSM)

configuration, can resonate in the interferometer [2, 26].

On the other hand, when Δ is comparable to δ, the average sideband light only sloshes once before leaving the interferometer. Because the sloshing adds a π phase shift to the sideband light, the interferometer behaves like a speed meter [27] — which has been sought for by the quantum-measurement community on grounds that speed is related to momentum, which for free mass is a so-called Quantum Non-Demolition (QND) observable [28, 31].

Variable Reflectivity Signal Mirror The signal recycling mirror can be replaced with a Fabry-Perot cavity. This tunable cavity will change the effective reflectivity of the signal mirror and allow for a tunable finesse for the signal cavity in addition to the usual signal cavity detuning phase. This can be realized either by an etalon, or by a Michelson interferometer, as has been demonstrated at the ANU [25]. This option is also naturally combined with the concept of a long signal recycling cavity.

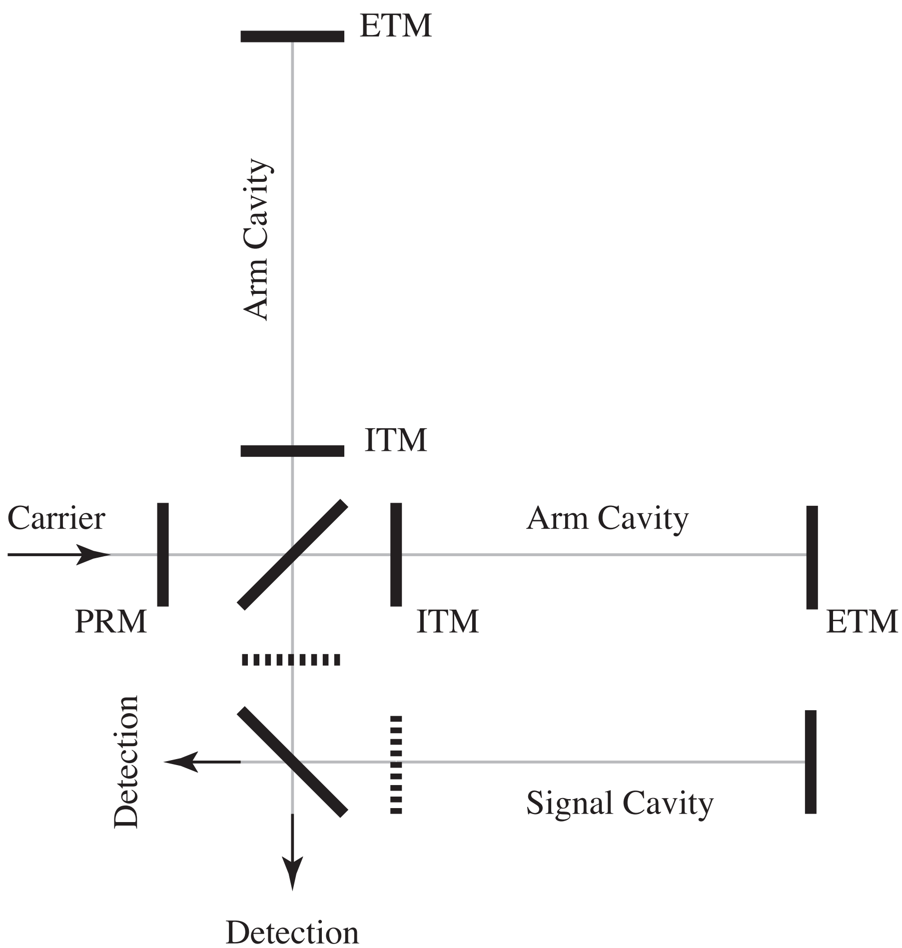

Figure 9: Fabry-Perot Michelson interferometer with long signal recycling cavity. Dashed lines indicate possible positions of signal-recycling mirrors.

4.1.4 Multiple Carriers/Optical Springs

Although we have long used multiple RF sidebands in order to do the length and angle controls of the interferometer, the use of multiple carrier fields (i.e. multiple lasers) has not been fully explored as a means of improving the sensitivity. Using a low noise phase locking servo, we can in principle, synchronize 2 or more independent lasers and use them to read out the GW signal, the auxilliary degrees of freedom, and to modify the opto-mechanical dynamics of the interferometer.

Multiple Carrier Fields Examples of such schemes are:

- Double optical spring [43] stabilization of the optomechanical instability, and further optimizations of configurations in which both carriers enter the arm cavities resonantly.
- Local readout [44, 45] improving low-frequency sensitivity of Advanced LIGO, in which one of the carriers does not enter the arm cavity, but simply reads out the motion of the ITMs.
- Use of a high power sub-carrier, injected from the PSL. This secondary laser would be set at one of the Free-Spectral Range (FSR) of the Power Recycling Cavity (PRC) and the arm cavities, but would be detuned in the SRC with the opposite sign relative to the carrier. This extra field can be used to *cancel* the optical spring [12].

These schemes can, in general, employ alternative wavelength lasers. The advantage of choosing a sub-carrier with an offset frequency less than ~ 1 GHz, is that the phase locking can be done with conventional electronics and that the mirror reflectivities are basically unchanged for such small changes in wavelength.

Intracavity Readout scheme This refers to configurations in which the gravitational wave signal is detected when a second carrier field (or some other sensing device) is used to measure the motion of a particular set of mirrors in their local inertial frames (see Ref. [46] and references therein). The word “intracavity” is used because it is assumed that the first carrier field does not generate useful output signals for readout.

The “local readout scheme” mentioned in the previous subsection can be regarded as an example of a mixture of intra- and extra-cavity readout. At high frequencies, the interferometer is dominated by extra-cavity readout, while at lower frequencies, it is dominated by intra-cavity readout. In the local readout example above, one may find it useful to use an alternate wavelength laser: the second wavelength can be made to have a very high finesse in the recycling cavities only, so as to maintain a high phase sensitivity for the ITM motion.

4.1.5 Ponderomotive Squeezing

Squeezing can be induced by mirror motion under radiation pressure — this is called ponderomotive squeezing. Although to date It has been more difficult than generating squeezing

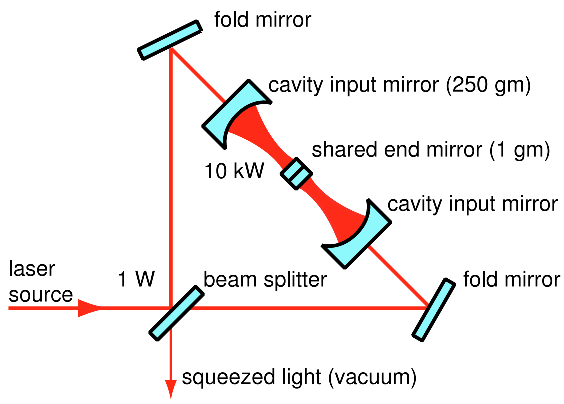

Figure 10: Ponderomotive Squeezer, taken from Corbitt et al. [48]

with nonlinear crystals, it may become more reliable and more flexible in the future. Currently a Ponderomotive Squeezing experiment is going on at MIT [49]. See Fig. 10 for a sample configuration.

4.1.6 Internal squeezing and slow light

Previously, it was proposed [51] to use gratings to broaden the frequency response of the SRC. In principal, such a "white light" cavity would have the high sensitivity of narrowband, tuned signal recycling with the wide bandwidth of detuned recycling. While the grating based approach has its problems alternate dispersive media may be more successful. Two approaches currently being developed are to use a negative dispersion material [52] (such as an atomic vapor) and to use a photorefractive crystal [53].

In addition to its possible use in broadening the signal cavity, dispersive materials may have use in squeezing applications:

- Atomic clouds or substrate doping can be used as a form of intra-cavity squeezer in the SRC.
- Electromagnetically Induced Transparency in an atomic vapor can slow down light, possibly improving high finesse optical filters [50]. In fact, with enough slowing, one can almost eliminate the need for long filter cavities.

4.1.7 Significantly different configurations

For example, Displacement-Noise-Free Interferometry (DFI) [57]. Although DFI might turn out not to be suitable for ground-based detection, there might be new ideas in this vein.

Then there is the general question of whether atom interferometry offers a competitive topology for a third generation detector.

4.1.8 Comparison among different advanced configurations

In the previous sections, we have discussed various advanced configurations that have lower quantum noise. Here we will consider those schemes that can be realized by adding additional optical components to the existing detectors without a drastic change in the topology. They are of particular interest because they can potentially be implemented for enhancing the sensitivity of the second-generation GW detectors in near term. We will focus on the quantum-noise part and optimize their sensitivity. By comparing their experimental complexity, namely the number of additional optical components required, we will get the guideline for selecting the appropriate configuration. Specifically, the configurations that we considered are the following [we summarize their features that are discussed earlier]:

1. *Squeezed-light injection with an input filter cavity*—it can rotates the squeezing angle such that both the low-frequency radiation pressure noise and high-frequency shot noise can be reduced;

2. *Squeezed-light injection with an output filter cavity*—it reads the optical quadratures in a frequency-dependent way and cancels part of the radiation pressure noise;

3. *Speed-meter configuration*—it introduces an additional cavity to slosh the signal back to the interferometer and gives a response to the test-mass speed at low frequencies;

4. *Long signal-recycling cavity*—it uses a longer signal-recycling cavity and can reshape the signal response in frequency;

5. *Dual-carrier field*—it includes an additional carrier light at a different frequency from the original carrier light, which provides us with an additional readout of the test-mass motion;

6. *Local readout configuration*—this is similar to the dual-carrier, apart from the fact that the second carrier light only resonates between internal test masses and the signal-recycling mirror, and can improve the low-frequency sensitivity.

To obtain the optimal sensitivity, we optimize their parameters with the following cost function:

$$\mathcal{J} = \int_{f_{\min}}^{f_{\max}} \log_{10}\left[\frac{h_{\rm AdvLIGO}}{h_{\rm LIGO3G}}\right] {\rm d}\, \log_{10} f. \tag{1}$$

It is inversely proportional to the gain in sensitivity of LIGO 3G compared with Advanced LIGO over a broad band in the log-log plot. The lower and upper bound for the frequency range $f_{\rm min}$ and $f_{\rm max}$ are chosen to be 10 Hz and 4000 Hz, respectively.

The optimization results are shown in Fig. 11. From the figure, we can learn that the squeeze injection with an input filter cavity can improve both the low-frequency and high-frequency sensitivity quite significantly. If an additional carrier field is included, we can further improve the low-frequency part by using the local-readout scheme, or improve the high-frequency part by using the dual-carrier scheme. For more details, one can refer to the AIC wiki [58].

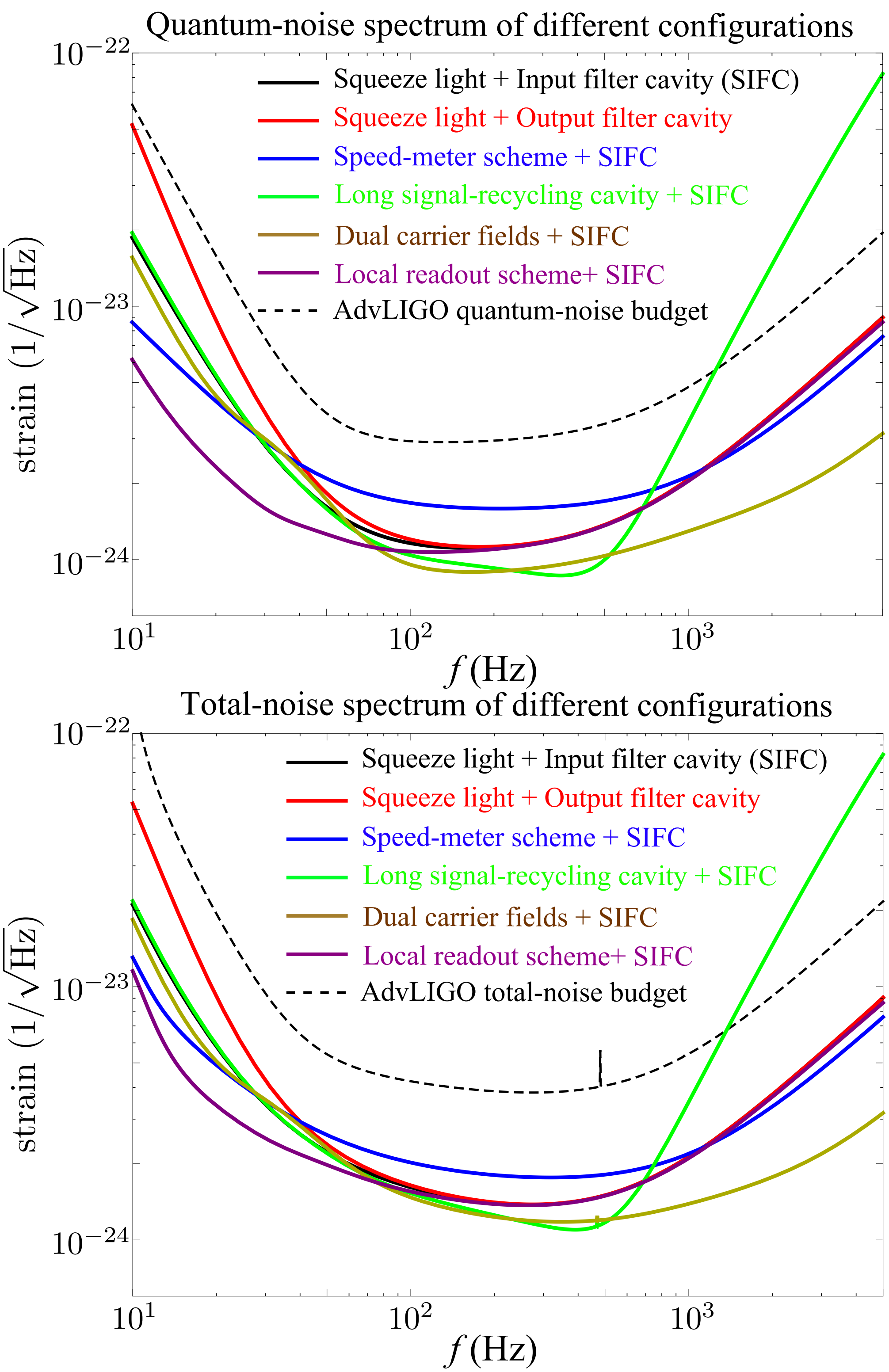

Figure 11: Comparison of the optimized sensitivity among different advanced configurations: the figure on the left side only shows the quantum-noise spectrum and the figure on the right side includes the technical noise that are specified in the gwincDev.

4.1.9 General Questions

Theoretically, advanced gravitational-wave detectors have two limitations, the *Standard Quantum Limit* and the *Energetic Quantum Limit*.

- *Is SQL-beating unavoidable?* The SQL arises from a trade-off between back-action and sensing noise — and more fundamentally it arises from the fact that light in the interferometer couple to the positions of free masses, which cannot be measured continuously without additional noise. The SQL sets the scale at which radiation-pressure noise and optical spring become important. The SQL can be avoided if we avoid sensing back-action, using back-action-evasion techniques. It can also be circumvented if we have optical springs. It can fundamentally be eliminated if we have mirrors with infinite mass. However, Will heavy mirrors be available? Which is easier, heavy mirrors vs. light mirrors with SQL-beating?

- *Can we surpass the Energetic Quantum Limit?* The Energetic Quantum Limit arises from Energy-Phase uncertainty relation (see, e.g., [64]) and basically describes the requirement for higher optical power when lower shot noise is desired. This can in principle be surpassed by optical springs. However, optical spring frequency is usually low, and does not reach frequencies in which shot noise dominate. However, can one do something to make it work? What about very light test masses coupled with heavy test masses, something like the optical-lever scheme?

4.2 Development of quantum radiation pressure dominated and QND apparatus

To date no experiment has observed quantum radiation pressure noise, let alone reached the 'naive' standard quantum limit. Such experiments are crucial to learn about problems which could mask such phenomena and how to beat such limits ahead of the operation of advanced generation detectors. To date there are major activities planned or underway at the AEI 10 m prototype; MIT; the University of Tokyo. The Glasgow 10m, the Gingin Facility and the ANU have embarked on testing optical spring dynamics. More effort is needed toward observing QRP noise.. As such experiments run up against excess noise sources and thermal noise they will inform activities across other working groups.

4.3 Experiments to prototype QND: filter cavities, variational readout, etc

Obviously, without QRP and SQL limited apparatus, no direct tests of these ideas can be performed. However, measuring transfer functions, demonstrating low loss manipulation of squeezed states an variational readouts can be performed with shot noise limited systems. Plans are underway for such an experiment at MIT and AEI. More effort is needed.

4.3.1 Loss Limitation

Optical losses might become more important when squeezing is used, or when internal ponderomotive squeezing is employed for sensitivity improvement (e.g. in schemes with output filtering).

The effect of losses is further amplified if back-action evasion is required, in which case the signal strength in the quadrature being detected is significantly less than conventional situations. A rule of thumb for this limitation is available from Kimble et al. [35], where we have

$$\sqrt{S_h/S_h^{\rm SQL}} \geq (e^{-2q}\mathcal{E})^{-1/4} \tag{2}$$

where $\mathcal{E}$ is the power loss, and e^{-2q} is the power squeezing factor. Assuming $\mathcal{E}$ to be 0.01, and 10 dB squeezing, we have a SQL-beating limit of 0.18.

For a given filter bandwidth $\gamma_{\rm filter}$ (to be determined by the needs of input/output filtering), when realized by a cavity of length L, the total loss $\mathcal{E}$ is determined by

$$\mathcal{E} = \frac{4\epsilon}{T} = \frac{\epsilon c}{\gamma_{\rm filter} L} \tag{3}$$

where T is the input-mirror power transmissivity [related to bandwidth by $\gamma_{\rm filter} = Tc/(4L)$] and ϵ is the loss per round-trip. It is therefore the ratio ϵ/L that determines the goodness of the filter. Since the per-round-trip loss ϵ depends on the beam spot size, which in turn depends on L, an optimization is need to find out the optimal length and design of filter cavities [41].

Practically speaking, ultra-low losses (around 1 ppm) have been achieved on the mirrors of fixed cavities [29, 30]. However, the lowest loss measured on the large, test-mass-sized beams are more usually in the 50-100 ppm range. FFT simulations have shown that the loss for large beams is dominated by the large scale figure error of the substrate, while the losses for small beams are dominated by point defects in the coatings. Since the low frequency performance of the QND schemes so strongly depends on the loss for intermediate sized (∼mm) beams, it is vitally important to develop ultra-low loss mirrors for this beam size. The modern polishing technology is already good enough.

Excess Noise Associated with atoms If atoms are to be inserted into interferometers, we must consider the excess noise induced by them. Since the main concern is with excess phase noise produced by the scatter, we should design and simulate the excess phase noise associated with these materials. The next step would be to demonstrate a higher optical phase sensitivity (increased signal without increased noise) at the $\sim 10^{-9}$ rad/$\sqrt{Hz}$ level.

4.4 Development of squeezed light sources

4.4.1 Crystal based squeezed light sources

For use as an early upgrade on advanced detectors or for mitigating against unstable high power operation, we require squeezing: 1) of greater than 10 dB (after accounting for propagation and detection loss) over the entire GW band, 2) stable over long periods of operation (days?) and 3) relatively free of non-stationery noise (glitches) is required. 4). In addition, immunity to scattered light may be important; and 5) high quantum efficiency photodiode are needed.

Great progress has been made over the last 5 years. 1) Both ANU and AEI produce such squeezers at both 1064nm and 1550nm (AEI only). By exploring ultra-low loss nonlinear materials and optics, optimising escape efficiencies, exploring doubly resonant designs, it may be possible to drive such systems towards 15 dB squeezing. Control of the phase angle becomes of vital importance. More effort at 1550nm is encouraged. 2) The GEO 600 has been operated now for days at a time; the ANU squeezer for hours (automatic re-locking required). 3) Iinvetigation of glitching is required. 4) Travelling wave resonators are inherently more immune to backscatter than Fabry-Perot based systems. 5) Photodiodes approaching 0.99 QE are now available. Further work could improve reliability and extend towards higher power handling.

4.4.2 Ponderomotive Squeezers

The only reported effort in this area is by MIT. The experimental development is closely connected with the construction of QRP limited devices. More effort is needed.

5 Optics

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 being installed in Advanced LIGO, to better understand their behavior during commissioning and operation, possible upgrades to subsystems of Advanced LIGO including core optics, input optics, and auxiliary optics, and longer term research into ways around significant limitations in current detectors to be implemented in the third and fourth generation interferometers.

5.1 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. The OWG contributed to the overall design of Advanced LIGO optics, including the selection of fused silica as the Advanced LIGO mirror substrate material and the selection of thickness optimized titania doped tanala/silica as the Advanced LIGO coating. There remain areas of research in the OWG to understand better what can be expected from Advanced LIGO optics and to make improvements in the planned optics for upgrades to Advanced LIGO.

5.1.1 Mirror 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 performance.

Doping and new materials Doping the tantala layers with titania has been shown to reduce mechanical loss. Titania-doped tantala/silica has been selected for the Advanced LIGO coatings. 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. Silica doped titania has shown promise for reduced thermal noise, and was considered a fallback coating for Advanced LIGO. A trinary alloy of titania/tantala/silica as the high index material may allow for benefits from each material. Different materials typically have different loss angles, so finding new high index materials for coatings holds the potential for improved thermal noise. It is crucial that any new material also satisfy the stringent optical requirements of LIGO interfereometers, but during a research phase there can be advantages of just pursuing lower mechanical loss. Silica, tantala, and titania have all be studied in some detail. There have been preliminary studies of other high index materials including hafnia, niobia, and zirconia. There are on-going and planned studies of the mechanical loss in these materials and its dependence on coating vendor, coating technique, annealing method, and doping. The dopants include silica, alumina, titania, and ytterbia. Hydrogen as a dopant has allowed for significant improvements in mechanical loss in silicon coatings and may allow for improvements in other amorphous materials. Characterizing the mechanical loss at a wider range of frequencies and temperatures will be valuable both as a search for new LIGO materials and to better understand the causes of thermal noise in amorphous thin film oxides.

Treatments and designs New treatments and designs, rather than materials, also potentially promise improved coatings. These include carefully chosen annealing processes, 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.

Since the thermal noise in the coatings typically scales as the total thickness of the more lossy material (although there are recent reports of mechanical loss being different in tantala with different thicknesses), 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 used in Advanced LIGO. Greater understanding of mechanical loss in thin film silica and/or other low index materials is crucial to exploiting the full potential of this optimization.

A new Young's modulus and dissipation measurement method with sub nanometer spatial and depth resolution developed by Konrad Samwer shows that the Young's modulus in glasses has a position dependent spread as wide as ±30% (and the local loss factor is also poorly defined), that the spread is reduced with annealing, while crystals have constant Young's modulus everywhere. It has also been shown that fused silica which is the glass with the lowest known mechanical loss, has a substantially narrower Young's modulus spread than other glasses. The method can either explore small shallow volumes, or wider and deeper volumes, up to several hundreds of atomic spacings in dimension. The capability of this method to scan the Youngs modulus with sub nanometric resolution offers a new way to explore the uniformity of our coatings, as a function of annealing, and perhaps shine some light on some loss mechanisms.

Variations in the loss of nominally identical coatings from different vendors have been observed, suggesting that the precise deposition parameters may be important in determining the loss. Thus more detailed measurements of the effects of parameters such as ion energy, sputtering ion, oxygen pressure and thermal treatment may be valuable. While ion beam sputtering produces the lowest optical loss coatings, the mechanical loss of coatings deposited by other techniques has not been extensively studied. Studies of coatings deposited by different techniques (e.g. magnetron sputtering, e-beam evaporation, atomic layer deposition) may enhance understanding of the relationship between loss and structure in these materials.

Amorphous materials, including fused silica, tantala, titania doped tantala, and other oxides under consideration as coating materials have two independent elastic moduli, and thus two independent loss angles. Recent work at Caltech by Yanbei Chen's group suggests that it may be possible to design coatings with reduced Brownian thermal noise by having the thermal noise generated by different loss angles partially cancel out. Whether this is practical or significant depends on the values of the loss angles for the coating materials, which can only be determined experimentally. Measurement of torsional and bulk mechanical losses of coating materials will provide necessary input for these designs.

Modeling of mechanical loss There is currently minimal theoretical guidance on what coating materials might have improved thermal noise. To help address this question, there is an effort underway to build 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 fairly well understood. After silica is successfully modeled, models of other dielectrics can be used as input when choosing coating materials. In addition, structural modeling techniques based on electron diffraction measurements, Reverse Monte Carlo methods and Density Functional Theory are being applied to coating materials. Initial results for tantala coatings show evidence of changes in the atomic structure due to doping and heat treatment which appear to be correlated with observed variations in the mechanical loss. Further experimental work on the dependence of mechanical loss on temperature, temperature history, torsional versus flexural motion, and frequency in coating materials would also help to better understand the source of the mechanical losses.

Theory of Coating Thermal Noise There has been progress in developing better theoretical models of thermal noise, given the experimental values of parameters like mechanical loss. The effects of diminishing optical power on thermal noise from coating layers closer to the substrate has been explored, and found to typically be a small but non-negligible effect. The effect of the finite size of mirrors, long overlooked or treated by numerical estimates, has been determined analytically. This theoretical effort has highlighted that our estimates of Brownian noise in 3G detectors (as well as Advanced LIGO) are not very firm. The inclusion of photo-elastic effects into the calculation of Brownian noise can provide us with new techniques by which to partially cancel the Brownian noise effect on the phase of the reflected field.

Optical Properties Absorption of the interferometer circulating light in the coatings will result in thermoelastic distortions of the optics and ultimately limit the circulating power. When coupled with the bulk absorption in the input test masses, 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 in 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. Detailed examinations of absorption of other potential coating materials will be important when considering their use in enhancements to Advanced LIGO or third generation detectors. However, progress can be made on improving coating thermal noise by working with relatively high absorption coatings (and vice versa) during a research phase.

Thermorefractive (dn/dT) and thermoelastic (dL/dT) effects in coatings are noise sources that are driven by the same (coherent) temperature fluctuations. Analysis 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 Caltech's 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.

Experience with scatter in first generation interferometers indicate there may be a need to develop coatings with lower intrinsic scatter. Examination of initial LIGO and Advanced LIGO coatings with a scatterometer are 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 near term Advanced LIGO procedures as well as for future instruments.

Direct Coating Noise Measurements In the past, the Thermal Noise Interferometer (TNI) at Caltech has measured directly the Brownian noise of coatings of the type used in iLIGO and aLIGO. As the Brownian noise calculation theory improves, it is key to measure the Brownian noise with increased precision and accuracy. Suspended interferometers like the TNI are not well suited to measuring the thermal noise in the low frequency band where it is most significant.

The next generation of thermal noise measurements will be done using fixed spacer cavities. These have been shown to be limited by coating thermal noise over a wide frequency band (f $\sim$ 1 - 1000 Hz) and are much easier to operate than a suspended system. These systems will use standard size (1 in. diameter) substrates and can provide a convenient testbed for the development of low thermal noise optics.

5.1.2 Silica Mirror Substrates

Experiments to measure mechanical loss in silica versus annealing parameters, including ramp down and dwell times have lead to improvements in the substrate thermal noise. In order for the fused silica thermal noise to pose a problem in the future, the thermal noise of the coating would have to be reduced by more than an order of magnitude. This seems unlikely within the time-scale of 3G detectors.

5.1.3 Parametric Instabilities

The build-up of parametric instabilities in the arm cavities related to the high intensities present in the arm cavities are potential issues from high optical power in Advanced LIGO. These undesirable effects result from exchange of energy between light stored in cavities and acoustic modes of the mirror which define the cavities. 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. High excitation of the mirrors acoustic modes can result in difficulties in the controls engineering and at very high amplitudes can lead to loss of lock. Unfortunately, the requirements for high sensitivity are commensurate with the conditions under which parametric instability occurs. These include high optical power and low mechanical loss materials in the mirrors.

Using finite element methods, it is possible to start developing a quantitative understanding of this problem by modeling the modes and parametric gain for different test mass configurations, as well as investigate methods for mitigating the instabilities. In order to make a realistic estimate for the parametric gain, it is necessary to also include the full field calculations of the dual-recycled interferometer [63].

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 (LASTI-MIT) 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 (Gingin-UWA). Outstanding questions include whether these approaches are compatible with high sensitivity, including low shot noise, low thermal noise, and realizable controls.

5.1.4 Charging

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 evidence from initial LIGO that charging of the optics has occurred and noise has visibly increased from hitting earthquake stops. There are several mechanisms by which the interaction between changes on the optic and charges on nearby surfaces can generate force noise on the optic. One noise mechanism is that a static charge distribution on either the optic or the earthquake stop will couple motion of the earthquake stop into forces on the optic [B. Lantz, T080214]. Another mechanism is the noise caused by time-varying charge distributions on the optic (or the earthquake stop) resulting in time-varying forces on the optic. Gaussian noise from this mechanism can be described by a Markov process [R. Weiss T960137-E]. The result depends on the magnitude of the deposited charge and the correlation time of the deposited charge, with a smaller fluctuating noise for correlation times far from the reciprocal of the frequency at which the noise is being measured. These correlation times are 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 and handling 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 to be used in Advanced LIGO causing noise or reduced effectiveness of the drive. Modeling has been started to study this, and experimental work at LASTI at MIT has begun to better understand the role of charge with 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.

A viable solution to the charging problem involves the use of nitrogen gas which is ionized externally to the vacuum chamber with an array of field point emitters [R. Weiss G1000383, Ugolini D, Funk Q LIGO-T1000135-v1]. The nitrogen ions, which comprise both polarities, travel through an aperture and into the vacuum tank. As this is essentially a thermally driven process, with charge on the optic attracting the appropriate polarity of ion to provide neutralization, it is unlikely that any damage to the HR coatings will occur, although tests are currently underway to assess this issue. A prototype system has been demonstrated at MIT and work is ongoing to test this technique on the monolithic noise prototype at LASTI. The discharge procedure would require approximately 1 day of downtime for the detector. In addition to the above technique, alternative discharge strategies are also being developed.

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. An interesting variation of this technique utilizes the fact that charging events arising from contact with earthquake stops will deposit charge in this local region. Work at Stanford is currently underway to develop a composite earthquake stop/UV-LED package. The benefit of this approach is that the discharge can be performed without the danger of illuminating the optic surface with UV radiation.

Experimental work on low energy ions as a way to mitigate charge without the need for UV exposure is also beginning. These ions can be brought into contact with the charged optic through either a partially directional gun or from a low pressure vent of the entire vacuum chamber. UV light is also being explored as a way to generate low energy ions, somewhat combining these two approaches. Work on utilizing a DC glow discharge to generate both polarities of charge carriers in Argon has also been shown to mitigate charge on the surface of fused silica. The technique uses a Faraday cup to maintain a neutral flow of ions which can be used to flow over the surface of the optic. Tests are continuing to assess whether this technique causes any damage to the HR coatings and to extend this technique to nitrogen gas.

There are other ideas being developed to measure charge and eliminate it as a problem for LIGO optics. Developing and testing finite conductivity coatings for the substrate of the surface of the test masses in order to: a) distribute the charge uniformly with a time constant of less than a few hours and b) allow discharging by "UV electron photoemission wireless" conduction. Work is progressing on a conductive layer composed of slightly reduced (i.e. oxygen deficient) tantalum pentoxide, and measuring the relationship between electrical conductivity, optical absorption, and mechanical loss. A "UV electron photoemission wireless conduction" system has been developed, and tests verify that it can ground the test mass to less than a 10 V potential. The UV source will consist of UV GaAs LED's and photoelectrons will be generated from the earthquake stops and from the facing surfaces on the side of the test masses. To reduce potential disturbances, no bias and or active controls will be used. Similarly, we have develop an electric field measurement system that meets following requirements: a) compatible with integration into the earthquake stops b) capable of measuring the potential of the test mass opposite the earthquake stops to an accuracy of equal to or better than 10 V. Further tests on the prototype aLIGO suspension will be pursued.

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. Torsion balances, which have been used for laboratory gravity experiments and to test noise models of LISA, offer another possibility to verify Markov noise from charges. Torsion balances are well suited to this since they reach their highest sensitivity at frequencies where Markov charge noise is expected to be large. 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 in the process of studying charging noise important to LIGO in this way. Additional torsion balance experiments are also being developed at University of Glasgow and Moscow State University. In Glasgow, a torsion bob comprising fused silica discs is being utilized to study charge motion on the surface of fused silica and the level of charge deposition when fused silica surfaces come into contact. A Kelvin probe located within the vacuum tank also allows the correlation time to be measured. Research at Moscow State University is focusing on the development of a high frequency (¿30Hz) monolithic torsion oscillator fabricated entirely from fused silica. This apparatus will be utilized to explore the space charge polarization induced when an Electro-Static Drive is operated near a fused silica test mass.

There is a wide range of charging research currently underway in the LSC groups. A viable solution to the charging problem for Advanced LIGO exists and additional backup scenarios are under further development. This work is performed in conjunction with the Suspensions Working Group.

5.2 Optics Research and Development for Fourth 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 enhancements to Advanced LIGO, it is clear that research on optical components for future ground-based interferometers must begin well in advance of any complete conceptual design.

5.2.1 New optics 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 and suspension connection techniques that must also be studied.

Silicon Research efforts on silicon have focused on acquiring and fabricating cylindrical test specimens and investigating their mechanical properties as a function of doping. Studies of silicon properties, including mechanical loss for predicting thermal noise, of different crystal orientations are valuable. 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 1550 nm and will need to be studied as a thin film.

Understanding the optical loss of silicon if used as a transmissive optic at 1550 nm 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 thermophysical properties will be important. 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.

Sapphire 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. Measurements of mechanical properties including mechanical loss as a function of crystal orientation are also important for predicting substrate and coating thermal noise.

Coatings It is vital to investigate the performance of the optical coatings as a complement to the research on new substrate materials. To take advantage of 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.

The thermal noise of the optical coatings is the fundamental limit for the aLIGO 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. While this increase in loss is not large enough to completely outweigh the benefits of low temperature operation, it does significantly limit the reduction in coating thermal noise likely to be achievable through cooling. 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.

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. With upconversion efficiency, it may be possible to produce green light directly from the aLIGO laser without greatly altering the noise properties. However, finding materials with suitable optical (absorption, scatter, thermo-refraction, etc) properties at the new wavelength will be an 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. High power, long-term exposure of coatings to any new wavelength will need to be performed under realistic cleanliness conditions. Scattering on the high reflective coatings can be expected to be different for shorter wavelength light than for 1064 nm light, and other optical properties such as the thermo-refractive index will need to be checked. Any optic with transmitted light (coatings, input test masses, beam splitter, Faraday isolator, modulators, etc) will have to be characterized for any new wavelengths and may need redevelopment. Finally, the effects of shorter wavelengths on interferometric operation (contrast defect, optical spring stability, etc.) will need careful consideration. This work is performed in conjunction with the Lasers and Auxilliary Systems Working Group.

5.2.2 Composite masses

Increasing the mass of the test masses reduces the influence of both classical and quantum radiation pressure noise. 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 influence of the Sidles-Sigg instability. Thermal noise issues related to mechanical loss from the interfaces will have to be resolved.

5.2.3 Diffraction gratings

All-reflective interferometers using diffraction gratings as optics avoid problems associated with the transmission of large laser powers through optical substrates. Moderately 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 can 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 investigated in depth. Investigations of mechanical loss in gratings are needed to verify thermal noise levels as are direct thermal noise measurements.

5.2.4 Coating-less or coating-reduced optics

These are some categories of ideas to remove coating thermal noise by removing the coatings:

- Corner cube style retro reflectors
- Brewster angle prism retroreflectors
- Khalili cavities as end mirrors (this one onl reduces the number of coating layers)

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. The new prototype interferometer at the AEI in Hannover is slated to test Khalili cavities as a way of reducing coating thermal noise.

6 Suspensions and Vibration Isolation Systems

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 isolation and suspension system for the most sensitive optics in Advanced LIGO 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 Hz. The final stage of the suspension consists of a 40 kg silica mirror suspended on fused silica fibers to reduce suspension thermal noise.

The R&D for all the Advanced LIGO isolation and suspension sub-systems has now been mostly completed, and assembly and installation are underway. There is still ongoing R&D work, which could serve for risk reduction, reducing commissioning time or upgrading the aLIGO vibration isolation and suspension. This work is discussed in Sections 6.1 and 6.2. The R&D for the 4th generation detectors is discussed in Sections 6.3 and 6.4.

6.1 Vibration Isolation R&D for aLIGO and aLIGO upgrades

6.1.1 Current status and ongoing work

The hydraulic pre-isolation stage (HEPI) is in place at LLO and is being installed at LHO. 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. Both types are currently under assembly and test, with the first BSC-ISIs due to be installed at LHO in late summer, and the first new HAM-ISIs due to be installed at LLO in early autumn. A BSC-ISI is installed at LASTI where it is being used in tests with the quadruple suspension prototype.

A pair of the single-stage HAM ISI systems for Advanced LIGO have already been commissioned at the observatories as part of Enhanced LIGO. A third HAM ISI system will also be built and delivered to LASTI for further development and Advanced LIGO integration testing.

6.1.2 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 and is a basic limit to the performance of the isolation systems at low frequencies (below ∼0.3 Hz) [65]. The aLIGO ISI 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.

Several methods of addressing tilt issues are being pursued. We are developing sensors to measure the rotational acceleration of the ground or of stages of the seismic isolation system in vacuum, which could be used to subtract the rotational component out, creating a purely translational horizontal sensor. Several rotational sensors are being investigated:

1. pairs of differential vertical seismometers, whose spatial separation would allow us to measure ground tilt [65].
2. Suspended bar tiltmeters are being investigated and these may also yield results on losses in different materials [66].
3. A laser gyroscope operating on the Sagnac principle is being developed. Unlike a traditional ring laser this gyroscope will use a passive cavity to avoid the effects of fluctuations in gas pressure [67].
4. Suspending a horizontal seismometer. This approach is distinct from the others in that the the seismometer is made to passively reject tilt noise, thus producing a tilt-free horizontal sensor [68].

When development of these various techniques for addressing tilt-horizontal coupling issues is further advanced a comparison of their relative merits for application to future detectors can be made.

6.1.3 Seismic Platform 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 [11].

The systems under investigation are slightly different; the method involves controlling the relative motion of the optical tables, and hence an alternative name is 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.

At the AEI 10m prototype, the SPI is based on a set of Mach-Zender interferometers, and use a LISA style phasemeter for readout [69]. The rotational degrees of freedom (DOFs) are sensed via differential wave-front sensing. The target sensitivity is 100 pm/$\sqrt{\text{Hz}}$ and 1 nrad/$\sqrt{\text{Hz}}$ at 10 mHz for displacement and rotational DOFs respectively.

It should be noted that improved rotational sensing described in Section 6.1.2 and the SPI are complementary approaches to the low-frequency noise issue. It is also important to realize that since the optical tables for Advanced LIGO are controlled in all 6 degrees of freedom, once 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.

6.2 Suspension R&D for aLIGO and aLIGO upgrades

6.2.1 Multiple pendulum suspensions - mechanical and control aspects

The quadruple suspension design for the test masses in Advanced LIGO [70] is based on the triple pendulum suspensions developed for GEO 600. The suspensions for the most sensitive mirrors (those hanging in the BSC chambers) have been built in the UK by a team. 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 are underway, with assembly, installation and operational checks plus development of novel control strategies for local and global control including modal damping and hierarchical control.

Testing of adaptive control schemes are underway to automatically adjust the trade-off between damping strength and feedthrough of sensor noise in the GW band.

Also planned are tests to study damping methods of the bounce and roll modes within the monolithic section. Methods of stiffening and damping resonances of the support structures of the suspensions to mitigate any adverse effects on the control systems of the active platforms are also under current investigation. Some risk-reduction characterization, with potential for incremental design improvements, will continue.

6.2.2 Development of monolithic final stage

Characterization (strength, dimensions, mechanical loss) of fused silica fibers as suspension elements [71, 72], produced using both oxy-hydrogen and laser-based pulling techniques [73], is well underway, as is development of welding techniques and silicate bonding techniques including characterization of associated losses [74]. There has also been a lot of work carried out on the ear shape and fiber shape including the neck region. ANSYS modeling has been used to localize the bending energy and to optimise the fiber shape to minimize thermoelastic noise, and to calculate the expected contribution of the silicate bonds to the thermal noise [75].

A full scale aLIGO monolithic suspension has been successfully incorporated into the noise prototype quadruple suspension at LASTI [76]. We are on track for installing the first monolithic suspensions in aLIGO at LHO for the one arm test later this year.

Several areas of research could yield enhancements to Advanced LIGO suspensions. Further understanding and characterizing of losses in silica fibers including investigations of nonlinear thermoelastic noise and of surface losses could lead to improvements. Changes in fiber neck shape including shorter neck and thicker stock could lead to enhanced thermal noise performance.

Research is also underway to further understand the role of weld loss in addition to techniques to observe and ameliorate stress in the weld regions. Furthermore, an increase in strength of the fibers could allow reduction in cross-section and in vertical bounce frequency, enhancing isolation. Investigations of the silicate bond mechanical loss and strength as a function of time and following temperature treatments are underway to reduce further the loss contribution and optimize ear design.

6.2.3 Newtonian Gravitational Noise

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 Gravitational noise.

Newtonian noise refers to fluctuations in the local gravitational field due to the motion of the nearby masses. Such fluctuations will perturb the interferometer mirrors, increasing the overall noise floor of the detector. Several theoretical studies [77, 78, 79] 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).

Earth's 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 subtract an appropriate signal from the strain signal so as to reduce to some significant extent the motion due to the Newtonian noise. Several studies are needed to assess the feasibility of this approach [77]:

- 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 expected that the bulk contribution of the (underground) seismic waves is about 10 times smaller in amplitude than that of the surface seismic waves. Consequently, it may be necessary to include underground seismic stations in the instrument array. The above measurements and model should address this issue, and suggest possible approaches.
- A similar effort should be pursued to address atmospheric fluctuations. This includes a monitoring array as well as modeling of the atmospheric density fluctuations.

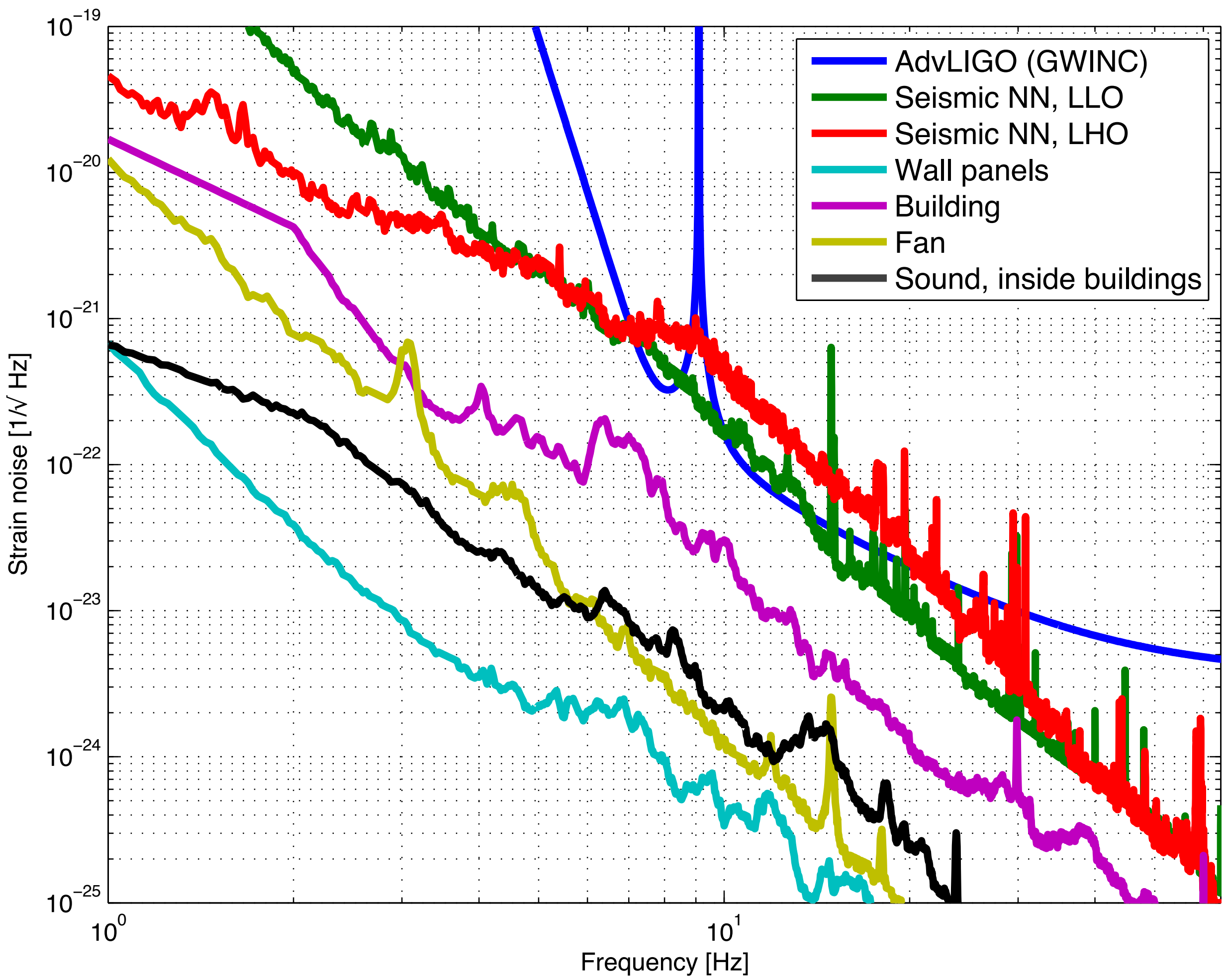

Figure 12: Newtonian Noise estimate for aLIGO [80]

- 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.

6.2.4 Violin mode damping

The silica fiber 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. A prototype optical violin mode sensor has been successfully tested on a dummy suspension with silica fibers at LASTI [81, 82]. However the decision has been taken not to implement violin mode sensing in this form in Advanced LIGO. The need for violin mode damping has not been demonstrated and if it is found to be required we can use Arm Length Stabilisation (ALS) system as a sensor.

6.2.5 Mechanical Upconversion: Crackling Noise

Some sources of detectable gravitational waves are expected to produce 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 fibers has been carried out with no non-thermal noise being seen at modest sensitivity (insufficient to exclude it as a significant noise source for aLIGO). Work has been done to study the noise associated with the violin modes of the silica suspensions in GEO 600 [83]. Further work is needed to extend these studies by modeling to put upper limits on the expected noise in Advanced LIGO. 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. 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.

Experiments of this type are envisaged or underway to measure or put upper limits on noise from maraging steel cantilever blades and separately from silicate bonds.

6.2.6 Low noise cantilever blade springs and improved suspension thermal noise

Development of fused silica blade springs which could be incorporated in the final monolithic stage for improved vertical isolation compatible with lower thermal noise is an attractive option to explore for possible upgrades to Advanced LIGO and future interferometers. Silicon and sapphire are also possible material choices. Experiments are already underway to investigate the breaking stress for such materials when used as blades.

Partial cryogenic cooling of the final stage of the suspension (blades and fibers) with a room temperature mirror is under consideration. There is also the possibility of using cryogenic Si blades. According to the literature, they should be very good if we can figure out how to make low vibration heat links.

6.2.7 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. Studies of low noise sensors such as interferometric sensors would be useful for enhancing the sensitivity of existing and new control systems [84].

6.2.8 Gas Damping

Work by colleagues in the LISA area and subsequent follow-up by LSC groups has shown that enhanced gas damping in small gaps could lead to excess noise in aLIGO suspensions [85]. The original design of the aLIGO quad suspension had a 5 mm gap between the test mass and the reaction mass used to apply actuation through electrostatic drive (ESD). We are mitigating this effect in aLIGO with a combination of a thinner compensator plate which forms the reaction mass for the inner test mass, leading to a larger gap, and by aiming to decrease further the pressure in the tanks where the end test masses are situated where the original gap size is needed to allow enough drive. In order to reduce this noise for future detectors we will have to consider alternative ESD or reaction mass geometries, or a completely new kind of actuator.

6.3 R&D Towards Fourth 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 within the scope of the SWG:

1. reductions in suspension thermal noise
2. improved seismic isolation
3. reduction of Newtonian Gravity Noise (a.k.a. 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.

6.3.1 Newtonian Noise: Underground

Newtonian noise 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 ($10^{-23}/\sqrt{\mathrm{Hz}}$) at this frequency.

One of the priorities for the 4G detectors is to probe frequencies below 10 Hz [77]. 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 4G detectors). We summarize below some of the directions to be explored.

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:

- Continue developing the array of underground seismic stations at the Homestake mine [86] (and preferably in other locations as well) 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.

6.4 4th Generation Suspensions

A range of techniques 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.

6.4.1 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 loss and bond loss. 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.

Attachment techniques A slightly modified version of silicate bonding for silicon-silicon attachment for, e.g., the attachment of interface pieces to silicon test masses is well underway. Strength measurements at both cryogenic and room temperatures of these bonds has shown it is a viable attachment technique and investigations are ongoing to further understand the influence of different parameters on strength like the nature and thickness of the oxide layer required. Bond loss measurements on silicon test masses have also started producing initial results.

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

6.4.2 Larger masses

Increasing the mass of the interferometer mirrors will linearly reduce the displacement noise due to (classical and quantum) radiation pressure noise. This research topic requires interfacing between the OWG (c.f. Section 5.2.2) and the SWG.

Particular challenges of a suspension system for such masses include maintaining low suspension thermal noise and high seismic isolation, incorporating actuation, and integrating such a system into a detector.

6.4.3 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. Investigations of materials suitable for construction of elements of the isolation and suspension systems with good properties for use at cryogenic temperatures should be studied e.g. silicon carbide which has good stiffness to weight ratio and low thermal expansion constant.

6.4.4 Magnetically Assisted Suspensions

An alternative approach to achieving suppression of seismic noise at low frequencies is to develop magnetically assisted suspensions. The basic idea is to use magnetic fields to partially cancel the gravitational restoring force in a pendulum. This can be achieved, for example, by deploying magnets of opposite polarity on the suspended mass and at the suspension point. The net result is to lower the spring constant of the system, and the corresponding resonant frequency. Preliminary attempts using ∼0.5m long magnetically assisted pendula have demonstrated resonant frequencies below 0.2 Hz (corresponding to ∼6 m long pendula) [87]. However, more detailed studies of such systems are needed to understand their applicability to future generations of detectors: tilt, angular degrees of freedom, chainability etc. Most significantly, it is not yet clear that such a system can be made to have low displacement noise in presence of Barkhausen noise.

7 Lasers and Auxiliary Systems

The Lasers and Auxiliary Systems (LAX) working group developed out of the Lasers working group. In addition to all types of *classical* lasers (squeezing is part of the Quantum Noise WG), this group now includes auxiliary systems which encompasses all technologies which are not part of any of the other working groups.

7.1 Advanced LIGO Pre-Stabilized Laser - Background

The development of the aLIGO prestabilized laser system (PSL) is effectively finished [88]. A four stage Nd:YVO amplifier system is used to increase the 2 W power of a Nd:YAG non-planar ring-oscillator (NPRO) to 35 W [89]. An injection locked Nd:YAG end-pumped rod system was chosen as the high power oscillator. An output power of more than 200 W was demonstrated in a linear polarized single spatial and frequency mode with such a laser system [90]. The laser has been developed and built by the GEO group in Hannover (Laser Zentrum Hannover (LZH) and Max-Planck-Insitut für Gravitationsphysik / Albert-Einstein-Institut AEI). The first laser system has been installed at LLO and the other two systems at LHO will follow soon.

The goal of the current phase is to provide technical support to the LIGO-lab and to monitor the long term stability of the laser.

7.2 Next Generation PSL

The laser sources required for 3G and 4G laser interferometric gravitational wave detectors depend strongly on the optical configuration chosen. Improvements in coating and substrate absorption, different substrate and coating materials and/or other operating temperatures, or new concepts such as all reflective interferometer could have much higher power handling capabilities than Advanced LIGO. Sagnac type interferometers might 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.

Therefore the research on lasers for future generation gravitational wave interferometer has to target many laser parameters including wavelength, power, spatial modes, and frequency stability.

7.2.1 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 operates 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.

7.2.2 High power concepts - solid state lasers

Different concepts are proposed to produce lasers with power levels of several 100 W 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 [91, 92, 93, 94]. 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 un-doped sections of the slab offers a scheme to deliver the pump light into the slab. If the interferometer design indicates that kW power levels will be required for future generation interferometers the power scaling has to be demonstrated and kW lasers have to be available early on for long term tests and for the development and tests of other optical components.

Efficient birefringence compensation can reduce problems caused by depolarization and by defocusing [95]. Hence the power range in which rod geometries can be used can be 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 end-pumped laser rods or slabs can dramatically be reduced [96, 97, 98]. 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% [98, 99, 100, 101]. 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.

7.2.3 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 [102, 103]. 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 [104]. 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 [105]. Further research in this direction might lead to a much simplified combined laser/modecleaner system for future gravitational wave detectors.

7.2.4 High power concepts - spatial mode filtering and adaptive optics

To convert distorted laser beam profiles into the target Eigenmode of the power recycling cavity either static or dynamic wave front correction systems or passive filtering will be required. Advanced LIGO uses optical cavities (the mode cleaner) to filter the fundamental 00-mode and suppress all higher order modes. This technology is slowly reaching its limits as the high power build up inside these optical cavities starts to distort the filter cavities themselves. Other spatial modes such as Laguerre Gauss 33-modes or Mesa beams require modified filter cavities which are resonant only for these specific spatial modes.

For higher power levels intrinsic problems are expected with the filtering method and hence dynamic adaptive beam correction methods should be designed. These could be based on well known Shack-Hartmann detectors and adaptive optic techniques currently employed in astronomical telescopes. These techniques have also significant commercial potential for many other high power laser applications.

7.2.5 High power concepts - alternative wavelengths

Laser sources with at different wavelength might be required for future 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 optical 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-Sapphire 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 [106] and almost 10 W were achieved in a SHG experiment using an infrared fiber laser [107]. It is also recently reported that 134 W of 532 nm light with 97% in the fundamental mode was generated by frequency doubling the Advanced LIGO 200 W laser system using an external optical resonator comprising a lithium triborate (LBO) crystal [108].

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 2 W 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 future generation gravitational wave detectors one of these designs can be chosen 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 1550 nm light source with a power level of 50 W.

7.2.6 Auxiliary Lasers

Auxiliary lasers serve several functions in interferometric gravitational wave detectors.

- CO_2 lasers at 10μm are used to write a heating pattern into the compensation plate placed next to the ITM.

- Diode lasers at various wavelengths are used together with Hartmann sensors to sense thermal deformations in the test masses and the compensation plate.
- Frequency doubled Nd:YAG lasers are injected at the end stations for lock acquisition.

The status and planned R&D on these laser types is described as part of the subsystems they are used in: CO2 lasers as part of the TCS actuation in Section 7.3, diode lasers for Hartmann sensors as part of TCS sensing and control in the AIC working group (Section 3.2.3). The AIC is also responsible for lock acquisition using aux. lasers (Section 3.2.1).

7.3 Thermal Correction System

The goal of the Thermal Correction System is to optimise the spatial mode inside the interferometer. This spatial mode can be degraded by imperfections in the mirrors caused by radii of curvature or surface figure errors as well as non-homogeneous heating of the optics by the science beam. Untreated, this will reduce the mode matching between the two arm cavities and the recycling cavities and change the beam size inside the interferometer. Advanced LIGO uses ring heaters to optimise the radii of curvatures of the ITMs and ETMs and CO2 lasers to compensate the thermal lens in the ITM substrate by acting on the compensation plate [17]. The current assumption is that the quality of the mirrors is sufficient that non-radial symmetric corrections are not required.

7.3.1 Ring Heater

The ring heater has to meet several requirements. It has to generate a homogeneous heating profile with minimal heating of the suspension structure. It s location very close to the test masses requires that it has to meet very stringent cleanliness requirements. CalTech has developed a ringheater which uses nichrome wire wound around a bended glass rod while the UF group developed a ring heater which sandwiches the nichrome wire between two alumina coated aluminum surfaces [110]. Both heaters are embedded inside a gold coated thermal shield to maximize the heat transferred to the mirror and minimize the radiative heat transfer into the suspension.

One way to reduce the heating by the ringheater or even eliminate it is to coat the barrel of the optic with a thin layer (a few microns) or an IR reflecting metal such as gold [17]. This would reduce the radial heat flow and homogenize the temperature distribution inside the substrate. 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. Gold coating applied to the barrel for thermal compensation purposes might 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, should be explored. 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 an upgrade to Advanced LIGO.

7.3.2 CO2 laser

Power fluctuations of the CO2 laser are one of the dominant noise sources associated with the TCS. Commercially available CO2 lasers do not meet the stringent requirements on power stability for Advanced LIGO during high power operation (125W input power in the science beam) and R&D has started to develop better CO2 lasers.

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 to correct non-radial symmetric beam distortions. Such a system could either be an enhancement for Advanced LIGO or for third generation detectors. This will require research on carbon dioxide or other potential heating 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.

7.4 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 around $10^{-9}/\sqrt{\mathrm{Hz}}$ in the interferometer input beam. The accurate sensing of the needed 500 mW 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.

7.4.1 Photodiodes

Advanced LIGO is currently using four in-vacuum photodiodes in parallel to measure the required 500 mW of light [111]. This is a sub-optimal arrangements for several reasons including reliability and alignment issues. 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 efficiency 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.

7.5 Electro- and magneto-optical devices

7.5.1 Electro-optic modulators

The length and alignment sensing scheme relies heavily on the generation of optical sidetones which co-propagate with the carrier field into the interferometer. These sidetones are currently generated by RTP-based electro-optic modulators which withstand several 100W of continuous laser power without degrading the beam profile. Future gravitational wave detectors are likely to work at different wavelengths and also at higher power levels for which suitable electro-optic modulators are not yet available or have not been tested. The main problems encountered in high power applications are photo refractive damage and variations in optical path length across the beam profile caused by the residual absorption of the laser beam. Photo refractive damage has a fairly well defined threshold in specific nonlinear crystals and can be increased by doping the crystal. The most promising family of crystals in the near infrared region are crystals belonging to the $MTiOXO_4$-family such as RTP; M is an alkaline metal such as K, Rb, or Cs, and X is either P or As. These crystals have fairly large electro-optical coefficients, good thermal properties, and, in principle, very low optical absorption coefficients between 1 and 1.6 um laser wavelength. Optical absorption in the $MTiOXO_4$-family increases at lower wavelength and potentially limits the laser power to a few 10W for visible lasers.

β-barium borate (BBO) and its derivatives are often used in the visible and near-UV region of the spectrum. BBO is uniaxial and has a very high damage threshold. Values larger than 3 kW/cm^2 for cw-light have been quoted by multiple vendors. It's negative thermo-optical coefficient prevents self-focusing. However, the electro-optical coefficient is low compared to other electro-optical crystals and BBO appears to be of limited value unless the laser wavelengths is reduced to well below 500 nm.

Magnesium-oxide doped lithium niobate ($MgO{:}LiNbO_3$) might be a potential alternative for IR lasers. The doping increases the photo refractive damage threshold significantly [112] and the crystal has a $\sim$10% larger modulation coefficient than RTP. However, going to laser powers beyond 1kW and laser wavelength below 1 um requires significant testing of electro-optical materials to ensure that electro-optical modulators will be available in time for third generation detectors.

7.5.2 Faraday isolators

Faraday isolators are required to separate the counter-propagating beam from the incoming beam. The aLIGO Faraday isolators use TGG as the Faraday material. The TGG rotates the polarization angle by an amount proportional to the length of the crystal, the Verdet constant, and to the applied magnetic field. The main issues with the Faraday isolator are beam distortion due to laser heating and subsequent thermal lensing, a reduction of the optical isolation due to depolarization and changes in the temperature dependent Verdet constant. This is further complicated by the fact that the FI is usually placed inside the vacuum chamber following the suspended input optic mode cleaner.

The aLIGO Faraday isolator uses two TGG crystals, a quartz rotator, and a waveplate to compensate the depolarization inside the TGG crystals. The radial symmetric thermal lensing is then compensated with a DKDP crystal which has a negative thermo-optic coefficient. Scaling this to kW-class power levels requires further reductions in the optical absorption in

TGG while the large number of components already increases the number of ghost beams significantly. Other options are to increase the Verdet constant by cooling the crystal, to use stronger magnetic fields, and to use other magneto-optical materials such as GGG or YAG.

Increased absorption in TGG will likely prevent us from using it at wavelength longer than 1.3 μm. But the telecommunication sector developed ferromagnetic rare earth iron garnets (RIGs) such as yttrium iron garnet (YIG) and more recently $\{BiRE\}_3(FeGaAl)_5O_{12}$ to rotate the polarization. Unlike paramagnetic Faraday materials, these ferromagnetic materials can be magnetized such that they don't require any external magnetic field. These materials are typically grown in sub-mm thick films on lattice-matched substrates such as GGG for 45 deg rotation. However, the absorption is still in the 1-10 ppm/cm range at interesting wavelengths which prohibits high power laser operation. At shorter wavelength, optical absorption increases in all materials pronouncing thermal effects. Faraday isolators using potassium dihydrogen phosphate (KDP) and its isomorphs have been developed for the UV but the absorption is still fairly high. A targeted research program to study these materials at higher power levels at all interesting wavelength is required to develop Faraday isolators for the next generation of gravitational wave detectors.

Faraday Isolator in Squeezing Systems The power handling capabilities of the output Faraday isolator are far less critical. However, the optical losses inside the Faraday would currently limit the amount of useable squeezing. Since squeezing is one of the leading ideas to upgrade Advanced LIGO, any improvement in the optical losses could directly improve the range of Advanced LIGO.

Figure 13 shows how the losses in the squeezed beam path are strongly affecting the amount of squeezing detectable in the interferometer and therefore the improvement in the sensitivity. With 10 dB of squeezing injected, for instance, the losses need to be less than 20% in order to be able to detect at least 6 dB of squeezing.

In a typical layout for injecting squeezing in the interferometer the squeezed beam needs to pass through not only the main output Faraday of the IFO (twice), but also at least one additional Faraday to isolate the interferometer from the squeezer and mitigate noise from back scattered light. The losses of the new Advanced LIGO Faraday have been measured to be $\sim$ 4%. Similar measurements in initial LIGO Faradays give losses of 4 - 6%. With the current losses the Faradays themselves will account for about 15% of the losses in the squeezed path. In order to maximize the benefit from the injection of squeezed light, it is important to reduce the losses of a single Faraday to 1 - 2%.

For the main dark port Faraday, it is also important to reduce the amount of light which leaks into the squeezed beam path, as this is a source of noise once it is back scattered back into the IFO from the squeezer source. In the new Advanced LIGO Faraday about 0.5% of the light which passes through the Faraday is reflected by the thin film polarizer. By improving the mechanical design of the Faraday one can hope to reduce this percentage down to $\sim$0.01%.

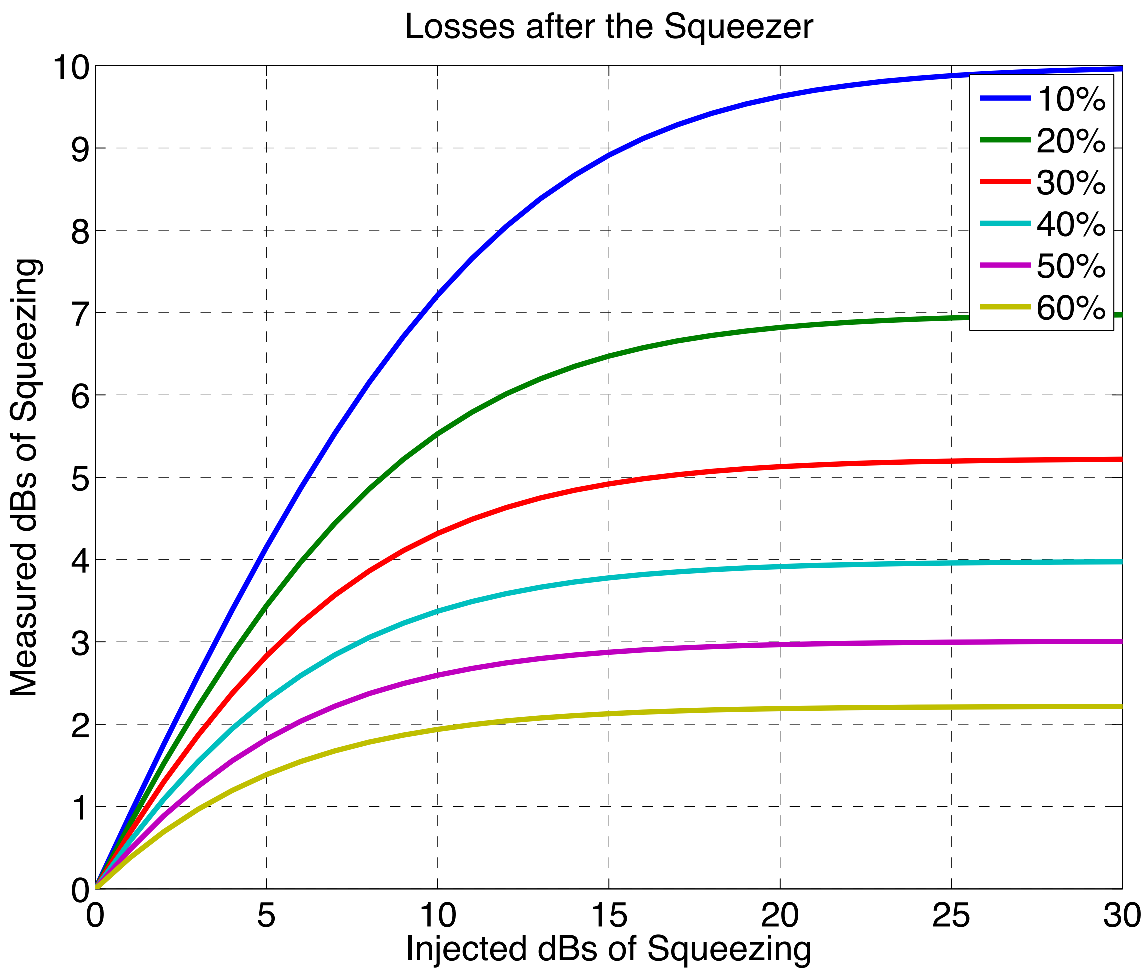

Figure 13: Measured squeezing as function of the injected squeezing for different levels of losses in the squeezed path.

7.6 Cryogenics

It has long been known that cryogenically cooled test masses can have much improved material parameters which lead to significant reductions in thermal noise. However, operating at cryogenic temperatures presents multiple new challenges which need to be addressed. The most pressing is to find ways to cool the temperature, to isolate the mirrors from their hot surroundings and to constantly extract the deposited laser heat without short-circuiting the suspension and seismic isolation system. Detailed thermal models have to be developed and tested to maximize radiative and conductive cooling paths.

An additional challenge 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. One idea which should be pursued is to use fs laser spectroscopy to identify the contaminant and potentially also to remove it.

7.6.1 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 to 1 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 a 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. Room-temperature experiments to explore this method of heat transfer have observed and are characterizing in detail the heat transfer in the near-field regime. Cryogenic experiments are planned, as are measurements 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.

7.7 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 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. It is possible 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 needs to 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 and experimental work is being carried out on Laguerre-Gauss and other optical modes that show promise for reducing thermal noise. Laguerre-Gauss modes may avoid some of the instability issues that cause concern with mesa beams. There are, however, questions about the strict requirements on the figure and polish of the optics necessary for these higher order modes. There has 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.

7.8 Other auxiliary systems

7.8.1 Photon Calibrator

The calibration of the interferometer requires to move the mirrors by a known amount and observe the changes in the gravitational wave channel. One way to apply the required forces to the test masses is photon pressure. This photon calibrator uses an amplitude modulated auxiliary laser which is reflected off the test mass. The integration, calibration, and performance of the photon calibrator is still an ongoing research subject.

A Mirror shape and composition

Thermal noise of the substrate and coating may be lowered if we consider mirror substrates and coatings with unconventional shapes and composition. On the other hand, in the quest for mirrors with large masses, we may have to consider composite mirrors made up from a smaller mirror with high optical and mechanical quality, but with the remaining part connected to the high-quality part in such a way that the total thermal noise and optical loss do not increase significantly.

A.1 Non-TEM_{00} modes

Three types of alternatives to fundamental TEM(0,0) modes have been considered, as summarized in table 1, also see the review article [59].

A.1.1 Higher Order Laguerre-Gauss Modes

One possible way to improve thermal noise is to use higher-order Laguerre-Gauss (LG) modes of cavities with spherical mirrors [7, 8]. These modes naturally have broader, and more uniform power distribution over the mirror surface. There is no need to modify the shape of the mirrors, although mirror radii of curvature should be adjusted (toward the *less degenerate* direction) in order that the higher LG modes now have the same loss as the fundamental $LG_{0,0}$ mode used to have. Experimental tests generating and resonating $LG_{3,3}$ modes in a short cavity has also been carried out [9].

These modes are intrinsically degenerate – and therefore may cause complications when applied to large interferometers [10]. We need to consider

- Whether we need to break the degeneracy intentionally, making the operating mode of the interferometer enough non-degenerate.
- Will the mode degeneracy be split naturally by figure errors in the polishing or the astigmatism caused by the gravitational sag?
- Can "corrective coatings" be used to intentionally "de-figure" the mirror surface?
- Can the outer ring of a composite test mass be used to apply stresses *in situ* to deform the mass and avoid unforseen degeneracies?
- How far out of the cavity linewidth do the higher order modes have to be split?

A.1.2 Modes supported by non-spherical mirrors

Mesa Beams. An *ad hoc* construction of optical modes that have lower thermal noise was to superimpose minimal Gaussian modes (i.e., those with waist at the center of the cavity and minimum spot size at the position of mirrors), with their symmetry axes either translated or rotated, to form a new mode with broader intensity profile at the mirrors. This resulted in the so-called Mesa beams, which are supported by Mexican-Hat mirrors [60].

Mode	Mirror Shape	Coating Noise Suppression Factor	Advantage	Disadvantage
LG(3,3)	Spherical	1.61	Spherical Mirrors	Degeneracy
Mesa	Mexican-Hat	1.53	Simple Construction	non-spherical mirrors
Optimal	Conical	2.30	Low Noise	non-spherical mirrors

Table 1: Alternative Optical Modes that have been considered for use in GW detectors, mirror shapes that support them, and their coating-thermal-noise suppression factors (in Advanced LIGO situation, namely 4 km arm length and 17 cm mirror radius).

Beam with minimum thermal noise. Work has been done to optimize over all optical modes with $m = 0$, and search for the mode with minimum coating thermal noise, keeping the same diffraction loss [61]. For a pure $m = 1, 2, 3$ modes, explorations show that only slight improvements can be made [62].

Further optimization. For reference, an unreachable (due to diffraction) theoretical upper limit of coating thermal-noise improvement can be obtained by assuming a uniform power profile, which is a factor 2.63 below the baseline Gaussian mode, or a factor 1.14 below the $m = 0$ optimal mode. This means additional optimization regarding thermal noise alone may not be possible. However, the beam with minimum thermal noise is shown to be very sensitive to mirror figure error. A subject of further research is to jointly optimize for coating noise and tolerance to mirror figure error.

Practical issues with non-sperical mirrors. Non-spherical mirrors, although can achieve lower thermal noise in theory, have not been used in high precision laser interferometry. We need to consider the following issues:

- Difficulty in manufacturing.
- Higher susceptibility to figure errors
- Difficulty in locking, and more stringent requirements on tilt and translation control.
- May require non-spherical mirrors for all input-output optics, e.g., mode cleaners, squeezers, etc.

A.2 Multi-Layer Coating designs

Coating Brownian noise might be lowered by altering the structure of the multi-layer dielectric coating. This will require further modeling of correlations in the coating taking into account anisotropic losses and, at least, a 2D model (cylindrical symmetry).

A.3 Composite Mirrors

Several (force) noise sources can be reduced by increasing the mass of the mirrors. It seems difficult to produce high quality mirrors with more than 100 kg mass. To reap the rewards of increased mass without producing larger mirrors, it may be possible to produce a heavy *composite* mirror.

A.3.1 Composite Mass

Purely as an example, one can imagine encasing the central (high quality) mirror with an outer donut shape made of low optical quality, but moderately high mechanical quality material. For example, the inner mirror could be a 100 kg fused silica of high Q and the outer donut can be a fused quartz ring. The interface can be made by a thin sheet of indium or gold. Of course, one would have to take appropriate care not increase the thermal noise.

Another example would be to do as above, but have the contacts be only at the points where the *ears* are on the existing mirrors. In this way, the thermal noise penalty is only as bad as the existing 2^{nd} generation suspensions.

A.3.2 Cavity/Etalon based

Two mirrors separated along their common optical axis, e.g., the Khalili cavity. Can we also combine this into the “optical configuration”?

B Straw-man configurations for LIGO 3G

In this section, we present two straw-man optical configurations for LIGO 3G, which assumes the classical-noise improvement cited in Sec. 2.1, and have broadband sensitivity. These have all been calculated using a development version of GWINC [4] called GWINCDEV.

1. Frequency dependent input squeezing (IS for short)
2. Frequency independent squeezing and output filtering (VO for short)

We list the parameters used in these configurations in Table 2, and plot their noise spectra in Fig. 14.

parameter	value
arm-cavity circulating power	730 kW
arm-cavity bandwidth	43 Hz
signal bandwidth (after RSE)	700 Hz
arm-cavity round-trip loss	100 ppm
photodetection efficiency	99%
filter loss per round trip	3 – 100 ppm
filter length	100 m
input squeeze factor	10 dB
squeezing injection loss	5%
test mass' mass	100 kg

Table 2: Parameters assumed for Straw-man configurations

C Macroscopic Quantum Mechanics with LIGO

Interferometers with classical noise budgets below the free-mass Standard Quantum Limit can be used to prepare (via cold-damping, radiation damping, or state collapse), evolve (in an optical-spring-induced potential well), and verify quantum states (through tomography) of macroscopic mirrors.

Techniques used to improve gravitational-wave sensitivity find corresponding roles in macroscopic quantum mechanics experiments, as shown in Table 3.

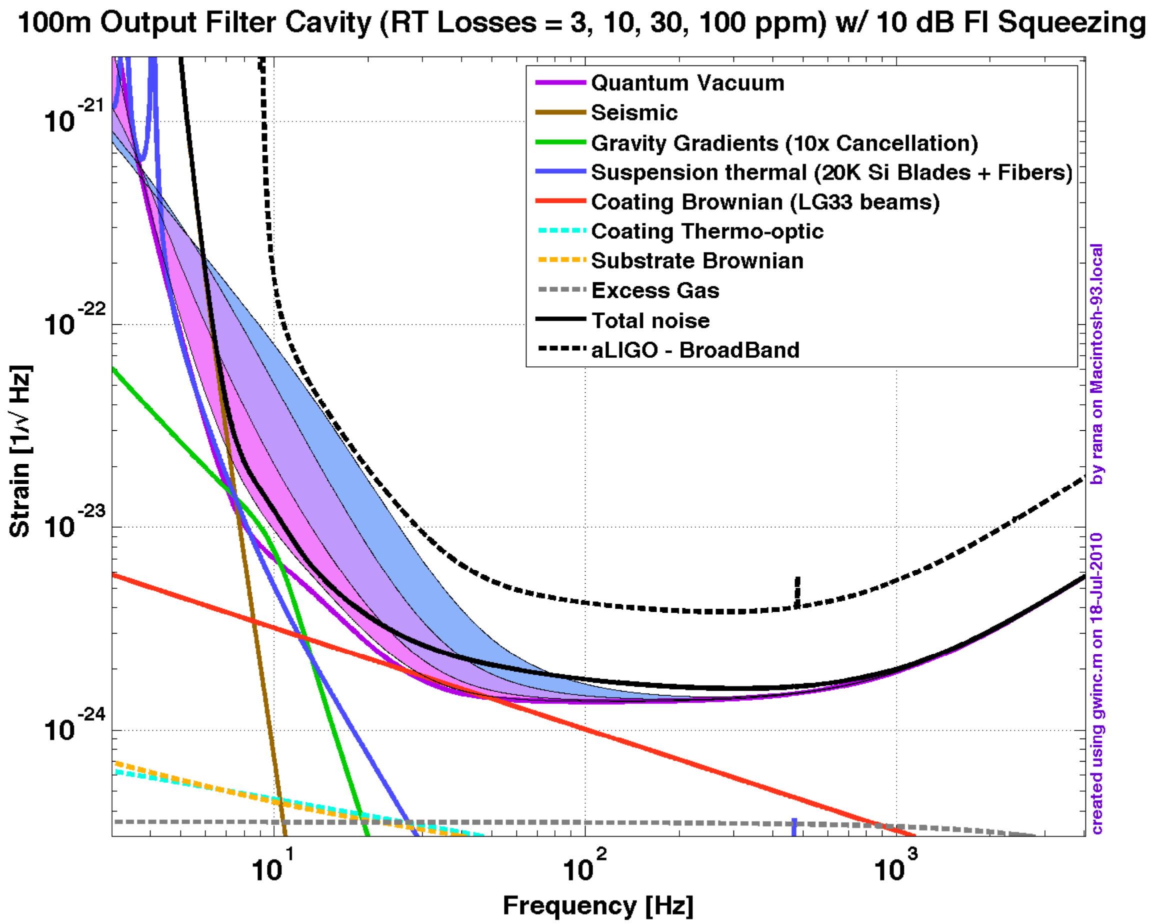

Figure 14: Noise spectrum using 10 dB of squeezing injection and a 100 m variational output filter cavity. The shaded regions indicate the low frequency quantum noise spectrum assuming RT losses of 3, 10, 30, & 100 ppm in the output filter cavity.

	GW detection	MQM
optical spring	resonant enhancement in sensitivity	trapping and cooling of mirrors
back-action evasion	applied in steady state avoid back-action noise	applied in transient improves state tomography
signal processing techniques	extract signals	obtain conditional mirror states in real time
control system	(hold device at operation point)	cold-damping state preparation
squeezing	suppress noise	flexibility in state preparation better sensitivity in state tomography
non-Gaussian optical states	(no applications yet)	prepare highly non-classical mirror states

Table 3: Corresponding roles played by the same techniques in improving GW sensitivity and in exploring macroscopic quantum mechanics.

D Advanced LIGO Installation Status

The project started officially in April of 2008 after years of focused research and development in the LSC. aLIGO is fully funded to date, is half-way complete in the formal project earned-value system, and presently on schedule to deliver three instruments (one at Livingston, and two instruments at Hanford, all 4 km long) capable of being locked for a few hours at a time by mid-2014. All of the subsystems have completed design except for some elements of the Auxiliary optics.

D.1 Overview of the Sub-Systems

- FMP The Facilities are changed to move the Hanford 2 km test mass chambers to 4 km, and the input-output tubes were increased in diameter to accommodate wider beam paths.
- SEI The seismic isolation is now more active, with servo-control systems to hold isolate against vibrations in the 0.1-10 Hz band.
- SUS The suspensions for the test masses have four pendulums in series (a quadruple design based on GEO-600 triple suspensions) with the final stage made of fused silica to reduce thermal noise
- PSL The pre-stabilized laser supplies 200 W (as compared with 35 W in eLIGO) of frequency, amplitude, and position stabilized light.
- IOO The input optics employ a similar configuration to initial LIGO but capable of handling the full laser power
- COC The test masses are fused silica, 40 kg to reduce the motion from radiation pressure noise, and 32 cm diameter to reduce the thermal noise. The coating is also optimized to reduce its thermal noise.
- AOS The Auxiliary optics include thermal compensation, baffling, initial alignment, photon calibration, and coupling of light out of the interferometer
- ISC A signal recycling cavity is added to the power-recycled Fabry-Perot interferometer to allow tuning for astrophysical sources and to manage quantum noise. There is a pre-lock arm-length stabilization system to aid and accelerate locking.
- DAQ The data acquisition system can handle the significant increase in channels due to the active seismic isolation and multi-stage suspension, and delivers low-latency data via several means.
- DCS The project includes a significant computing capability for the data analysis.

The ever-improving understanding of what we can actually build has not led to any significant changes inour expectation for the ultimate performance (see Fig. 2). There are now well-developed plans for the incremental approach to those curves. The first activity will be a single 4 km Fabry-Perot cavity at Hanford, locked with an Arm Length Stabilization system, with integrated testing starting in Spring 2012. The hardware elements for that are now being readied for installation, with a Quadruple suspension now mated to an internal seismic isolator; the arm-length stabilization system in assembly; and the full acquisition and control system available to support the effort.

At Livingston, we are gearing up to make a power recycled Michelson interferometer with the two near mirrors of the arm cavities as the initial integration focus, with integrated testing starting in Summer 2012. The laser at Livingston is installed and tested, and the input optics components are on the shared optics table. At both observatories, modifications of the vacuum system are underway larger input- optics tubes at Livingston, and moving chambers from the 2km to the 4km point for the second interferometer at Hanford.

D.2 Further Reading

- M060056: Advanced LIGO Reference Design
- G1000061: aLIGO Current Installation Schedule
- P0900255: Advanced LIGO: The next generation of gravitational wave detectors

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