LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Scientific Collaboration

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LSC Instrument Science White Paper 2010

LSC Advanced Detector Committee, for the LSC

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1 Introduction

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

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

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

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

There is also a very close link with the characterization of the completed detector; often the pursuit of an artifact in the data can only be explained by an instrument scientist, and often artifacts seen in the data inform instrument scientists of a heretofore unknown instrumental shortcoming. Thus, close coordination of the Detector Characterization and the Instrument Science working group is mutually rewarding. The Detector Characterization activities are addressed in the Data Analysis White Paper.

Broadly speaking, instrument science research efforts break down into three categories.

- Many of the LSC instrument scientists are playing central roles in Advanced LIGO. Most effort is on production of known designs, but there are also background tasks to better understand the designs, and to consider ways to modify e.g., software control laws to improve the stability or performance of Advanced LIGO. The time scale for research projects in this class to bear fruit is the next three to five years. We do not report Advanced LIGO Project activities in this report, as it is planned, supported, and carried out in a different model than the general Collaboration research program.
- Concepts for incremental but significant improvements to Advanced LIGO (“LIGO 2.5”) are starting to gel, and the working groups have some specific targets of opportunity that

appear to have promise for very interesting astrophysical consequences. Much of the forward-looking ‘research’ at this time falls in this category. We note that these activities will almost certainly play a role in mitigating unforeseen problems in Advanced LIGO, as our experience with initial and enhanced LIGO has shown us.

- On a longer horizon, there is a strong scientific motivation to probe gravitational waves in the frequency band 0.1-10 Hz. In addition to bridging the gap between space-based instruments, e.g., LISA (operating below 0.1 Hz) and Advanced LIGO/Virgo (operating above 10 Hz), this frequency band is expected to contain a number of sources that would be otherwise inaccessible. There is enthusiasm and commitment to create instruments which can realize these observational goals, and the GWIC Roadmap[1] for the future of the field shows the unity of purpose. The LSC intends to start the process of developing a conceptual design for third-generation instruments, and looks forward to collaborating with the European design study for the Einstein Gravitational Wave Telescope (ET).[2]

This white paper represents the current thinking of the LSC technical working groups as of mid 2010. It will undergo revisions periodically as we reassess the needs of LSC instrument science.

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

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

2 Advanced Interferometer Configurations

2.1 Introduction

The aim of the AIC Working Group is to carry out theoretical and experimental research for both short- and long-term upgrades/re-designs of ground-based gravitational-wave detectors. In this White Paper, we summarize a list of topics that will define the scope of research in our Working Group.

The core interest of the group is the “optical configuration", namely the design of the idealized device that only includes the longitudinal optical mode and the translational mechanical modes. However, this idealized interferometer only exists as part of a larger system, the entire interferometer. The idealized interferometer is limited by constraints imposed by design of the interferometer components (e.g., mass of mirrors, optical power, pendulum frequency etc.), and from residual coupling with other degrees of freedom. This coupling can be linear, and result in additional noise (e.g., laser noise, internal/suspension thermal noise, seismic noise, etc.); it can also be nonlinear, and result in a modification of dynamics, causing instabilities (e.g., tilt instabilities). Innovations in the science and technology of optics, light sources, suspensions, and isolation systems also serve as stimulation for new ideas on the overall design.

As a consequence, design of the idealized interferometer must be an interactive one, with other effects in mind. To be concrete, we divide our efforts into two parts: those involving an upgrade to Advanced LIGO (referred to here as LIGO 2.5), and those towards third-generation detectors (LIGO 3).

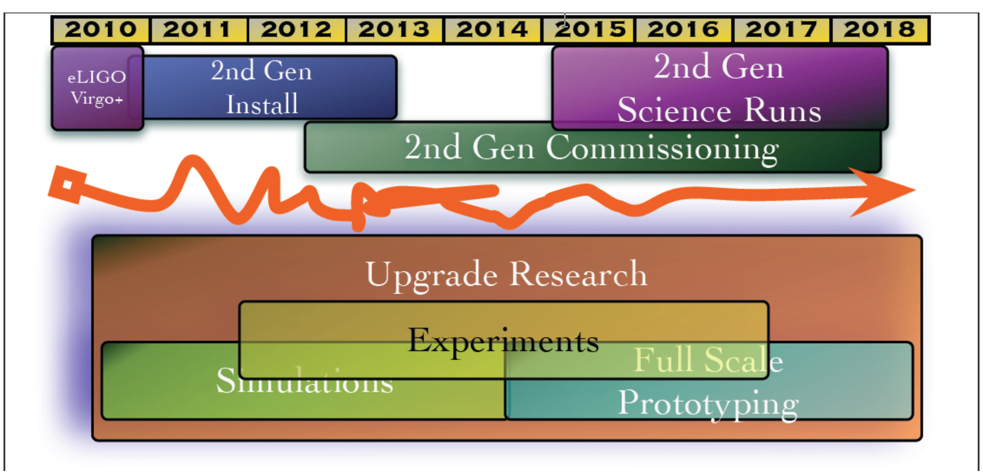


Figure 1: Timeline for Research into post-2nd-generation Upgrades

• For LIGO 2.5, we have a more concrete time line, with the aim of deployment starting from 2016. IF we imagine it to be similar to the LIGO 1.5 upgrade it would be required to be a modest upgrade (3 years / 50 million USD). This means we need to set our design within a constraint that is regarded as realistic for that time scale.

• For LIGO 3, designs of optical configurations with better sensitivity can help identify the particular need to improve certain areas. For example, the use of squeezed vacuum (especially if the Standard Quantum Limit were to be surpassed) may require a much more stringent tolerance to optical mode matching and optical losses.

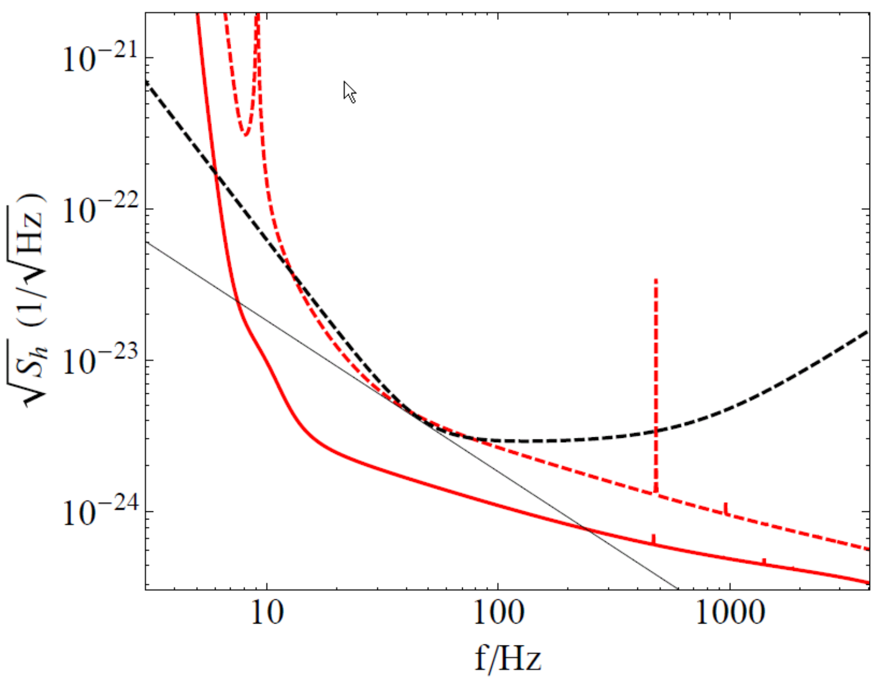


Figure 2: Total non-optical noise spectrum of LIGO 2.5 (red solid), as assumed in Sec.2.2.1, in comparison with the corresponding curve of Advanced LIGO (red dashed), as well as (broadband) quantum noise of Advanced LIGO baseline (black dashed).

2.2 Constraints

In this section, we identify, or rather, outline a program that identifies the constraints applicable to LIGO 2.5 and LIGO 3, respectively.

2.2.1 LIGO 2.5

In the LIGO 2.5 timescale, we mainly need to design optical configurations geared toward concrete constraints from somewhat reliable projections of other technical constraints. To be ready in roughly 2016, we would need to have the laboratory scale R&D begin within 1 year or so. Of course, its difficult to know exactly what upgrades will be most beneficial before the commissioning of Advanced LIGO reveals the problems. Lacking this knowledge, we can instead choose to develop those technologies that will produce a significant improvement in only the known limiting noise sources.

1. We may expect coating thermal noise and suspension thermal noise to improve modestly, leaving space for sensitivity improvement in the 5 – 50 Hz range. These require improvements in the test mass coating technology (e.g., materials) and upgrades of the suspension system. At the moment, it is important to push a research program that deals with thermal noise improvement. We need to have a clear idea of the plausible improvement rather soon. For the purposes of proceeding with the optical design we will assume an improvement of a factor of 2 in the coating Brownian noise amplitude spectral density (factor of 4 in the power spectrum). For some related technologies see sections 2.5, 2.6, and 2.7.

2. For the suspension thermal noise, will assume that the bounce mode frequency can be lowered by a factor of 3 with a concomitant reduction in the vertical mode thermal noise.

3. We will not consider major changes in the facility, nor can we significantly modify the mirror size. We also rule out cryogenic mirrors in this time frame.

4. It is possible that Newtonian noise mitigation through active noise cancellation would become realistic during this time scale. Therefore we assume a reduction by a factor of 10 of the Newtonian noise.

5. We may be able to modify the configuration by modifying the signal recycling cavity, possibly by elongating the cavity into 4 km.

6. There are optical configurations allowing the injection of squeezing, which may be filtered by cavities with moderate lengths (10's of meters), or even 4 km.

7. It may be possible to inject multiple carrier frequencies into the interferometer in order to shape the frequency response or to provide alternative means for controlling the length and alignment degrees of freedom.

Modeling activities involving these aspects should be completed within a few years, and should pay special attention to practical imperfections, and sensing/control issues. In Figure 3 we plot the non-optical noise spectrum of Advanced LIGO (red dashed curve), the Advanced LIGO quantum noise (broadband configuration, black dashed curve), and the total non-optical noise spectrum of LIGO 2.5 that corresponds to the above discussions (red solid curve).

2.2.2 LIGO 3

For LIGO 3, the constraints are less concrete, yet they certainly allow more dramatic improvement of sensitivity.

One of the major decisions affecting the design will be whether or not the 3rd generation interferometers are built underground. There are pros and cons to underground interferometers and we need to do a design study to compare the sensitivity of underground interferometers with ones utilizing the existing LIGO facilities.

1. System considerations. We need to explore different interferometer geometry.
2. We need to identify the potential for each of the critical technical aspects.

(a) How big can the mirrors / test masses be? Can large masses be supported by the suspension?

(b) How much lower can thermal noise in the coating/substrate be? Cryogenics? How?

(c) What can we expect for suspension thermal noise? Cryogenic fibers? Magnetic suspensions?

(d) What is the ultimate amount of power we can have / handle?

(e) What may be the level of Newtonian noise on the surface after subtraction? Underground?

(f) Can the gas damping be sufficiently mitigated in the future suspension design?

(g) Can atoms be added? What about Noise?

In planning third-generation detectors, we must also consider the astrophysical motivation. For example, for a particular candidate population, we need to seek information as to the possible gain of scientific pay-off corresponding to particular improvements of sensitivity.

2.3 Interferometer Topology Options

2.3.1 Optical Filtering and Strategies for Injecting Squeezing

2.3.1.1 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 [22, 23], which considered frequency independent squeezing. The use of optical filters to achieve back-action evasion originated from the variational readout strategy by Vyatchanin et al. in the time domain [24], 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:

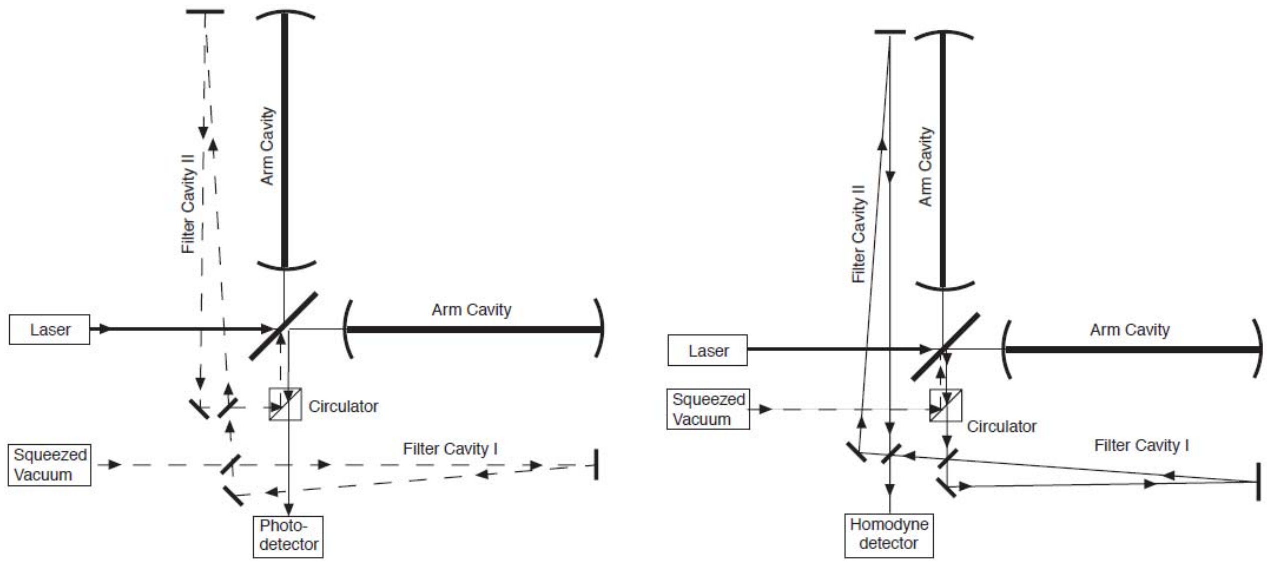


Figure 3: Frequency dependent input squeezing (left panel) and Frequency dependent homodyne detection (right panel) with optical filters. [Adapted from Kimble et al. [25].]

• Kimble et al. [25] designed Fabry-Perot cavity filters (with one coupling mirror and perfect end mirror) for optimal squeezing injection, as well as optimal readout, in broadband Fabry-Perot Michelson interferometers (see Figure 3 for layout of these configurations, as well as left panel of Figure 4 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 [17] into general quadrature rotation angles.

• Harms et al. [26], Buonanno and Chen [27], 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, yet failed to find filters that realize such angles.

• Corbitt et al. designed *amplitude* filters [28], 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 Figure 4.) They also considered serial and parallel amplitude filters.

• Khalili [29] substantially improved the amplitude filter by adding a homodyne detection at the open port – and subtracting this channel from the main detection channel with the appropriate gain. (See right panel of Figure 4) This was further developed [30].

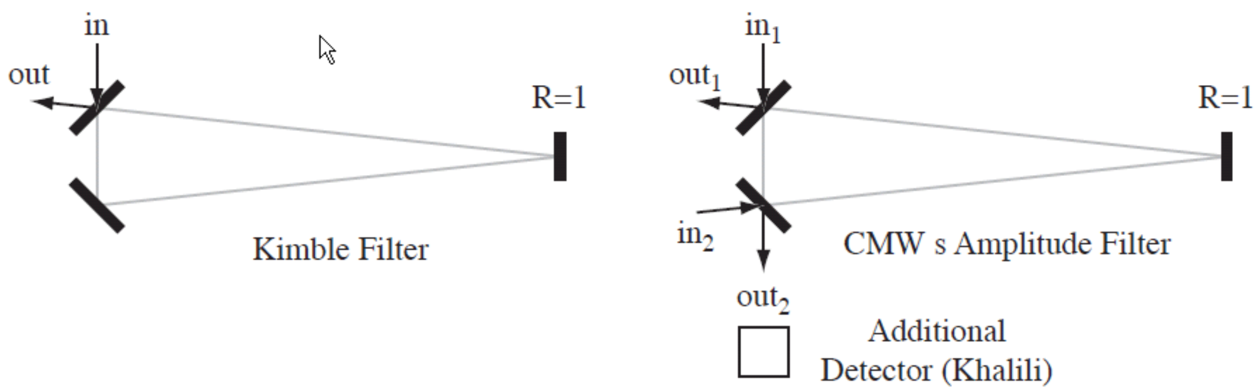


Figure 4: Left Panel: Kimble filters, with only one input and one output. Right Panel: Amplitude Filter proposed by Corbitt, Mavalvala and Whitcomb, and improved by Khalili, who proposed adding an additional homodyne detection.

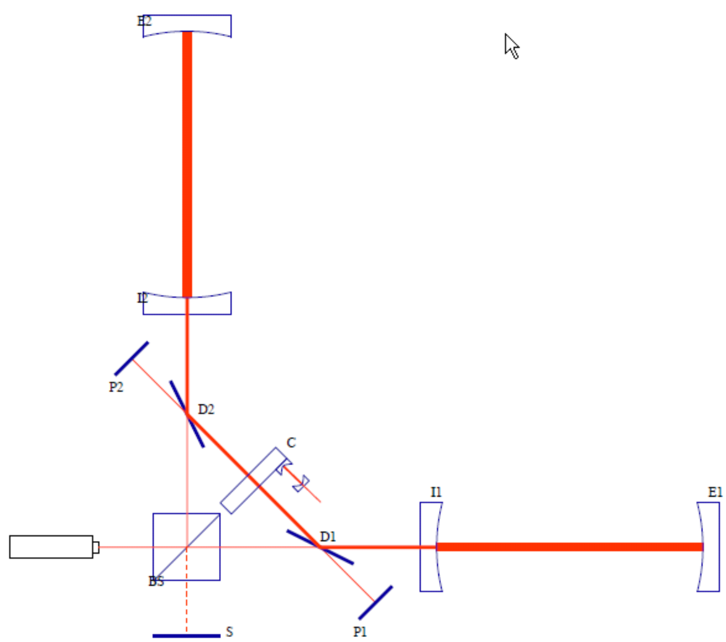


Figure 5: Interferometer with an intracavity readout scheme, taken from Ref. [36]. The GW signal leads to unbalanced forces on mirror C and that the motion of this mirror is then read out via the (unlabeled) local meter.

In general, input squeezing combined with output filtering, in idealized situations, 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.

However, 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 much susceptible to optical losses.

2.3.1.2 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. [25], where we have

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

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

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

$$\mathsf{E} = \frac{4\varepsilon}{T} = \frac{\varepsilon c}{\gamma_{\text{filter}} L} \tag{2}$$

where T is the input-mirror power transmissivity [related to bandwidth by $\gamma_{\text{filter}} = Tc/(4L)$] 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 [31].

Practically speaking, ultra-low losses (around 1 ppm) have been achieved on the mirrors of fixed cavities [19, 20]. However, the lowest loss measured on the large, test-mass-sized beams is 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.

2.3.2 Time-dependent Homodyne Detection

In a detuned interferometer, the GW signal appears in both quadratures of the output electric field. The sensitivity of 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.

2.3.3 Modifications to the Signal Recycling Cavity

2.3.3.1 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 [15]. This option is also naturally combined with the concept of a long signal recycling cavity.

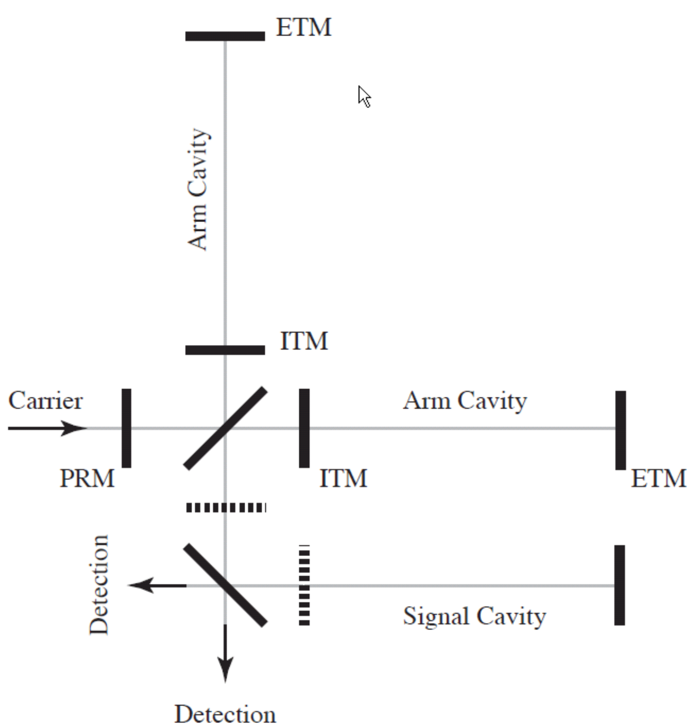


Figure 6: Fabry-Perot Michelson interferometer with long signal recycling cavity. Dashed lines indicate possible positions of signal-recycling mirrors.

2.3.3.2 Long Signal Recycling Cavity

The Advanced LIGO signal cavity is designed to be 50 m. It will be possible to extend this cavity to 4 km, as shown in Fig. 5. 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 be interesting in the following ways.

As shown in Figure 7, in an interferometer with a tuned long SR cavity, modulations to the carrier sloshes 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 can be described as “double signal recycling", in which both sidebands $\omega_0 \pm \Delta$, instead of a single sideband as in the usual signal-recycling configuration, can resonate in the interferometer [2, 16].

On the other hand, when Δ is comparable to δ, the average sideband light only sloshes once before leaving the interferometer. In this case, since the sloshing adds a π phase shift to the sideband light when it returns, the interferometer behaves like a speed meter [17] – which had 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 [18, 21].

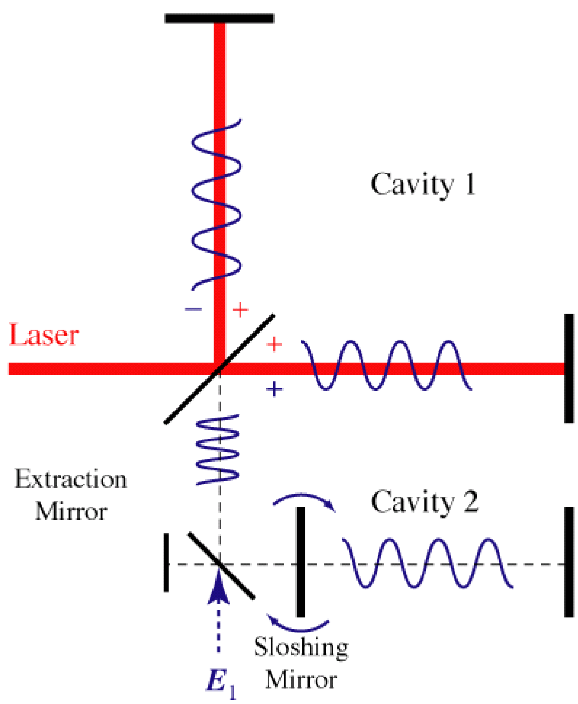


Figure 7: Diagram of a long SRC used as a Sloshing Speed Meter (SSM)

2.3.4 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 auxiliary degrees of freedom, and to modify the opto-mechanical dynamics of the interferometer.

2.3.4.1 Multiple carriers in the same interferometer

Examples of such schemes are:

• Double optical spring [33] stabilization of the optomechanical instability, and further optimizations of configurations in which both carriers enter the arm cavities resonantly.

• Local readout [34, 35] 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 [11].

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.

2.3.4.2 Intracavity Readout scheme

This refers to configurations in which gravitational wave 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. [36] and references therein). The word ``intracavity" is used because it was 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. In high frequencies, the interferometer is dominated by extra-cavity readout, while in 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.

2.3.5 Dual Band - Dual Interferometer

The trouble with making an interferometer with good low frequency sensitivity is often in the power handling:

• The radiation pressure torques require noisy angular control systems. Conversely, it is easy to design a very robust angular control system for a high frequency only interferometer.

• The high laser power deposits heat into the mirrors, complicating the design of cryogenic systems.

• Requiring low optical losses in mirror coatings overly restricts the design of low *mechanical* loss coatings.

• Technical and Quantum radiation pressure from high laser power produce excess displacement noise at low frequencies.

By having two interferometers per site, we can have a broadband sensitivity improvement. The high frequency interferometer can operate with modest seismic isolation, small mirrors, and MW scale arm cavity powers. The low frequency interferometer can be cryogenic, use heavy mirrors, use low thermal noise coatings, etc.

A similar solution has been outlined for the Einstein Telescope [37].

2.3.5.1 Suspension Point Interferometer

In a specialized case of the dual-band idea, the penultimate mass of the low frequency suspension chain serves as the test mass for the high frequency interferometer. In this scheme, the locking of the Penultimate Interferometer serves to isolate the Ultimate Interferometer from seismic noise. As has been pointed out by Aso [10] and others [46], the mechanical mismatch between the suspensions can limit this suppression. The initial LIGO experience has shown that we can achieve a 1% match with no special care, so probably we can assume 0.1% for 3rd generation systems.

This level of suppression would allow moving the seismic wall down to ~1 Hz. The technical advantages in operating from a highly stable platform are numerous and need not be listed here.

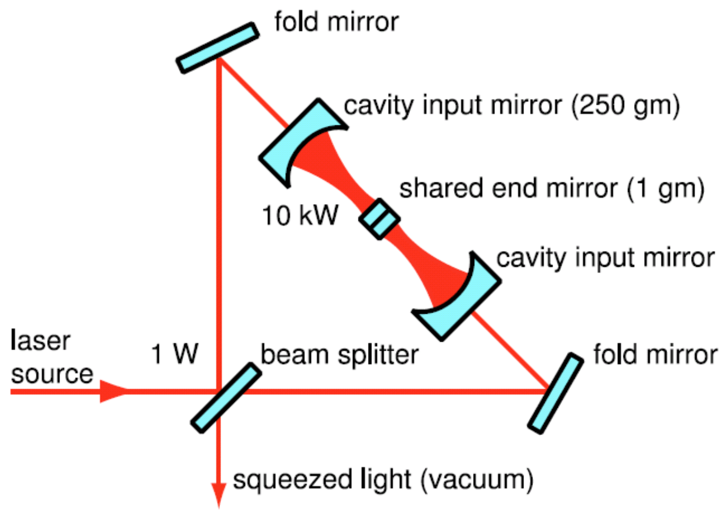


Figure 8: Ponderomotive Squeezer, taken from Corbitt et al. [38]

2.3.6 Ponderomotive Squeezing

Squeezing can be induced by mirror motion under radiation pressure – this is called ponderomotive squeezing. It has been more difficult than generating squeezing with nonlinear crystals, yet it may become more reliable and more flexible in the future. Currently a Ponderomotive Squeezing experiment is going on at MIT [39]. See Figure 8 for a sample configuration.

2.3.7 Atoms in Signal-Recycling Cavities

This is certainly a 3rd generation or beyond concept.

2.3.7.1 Internal squeezing and slow light

Previously, it was proposed [41] to use gratings to broaden the frequency response of the SRC. That approach has its problems. Another approach to a ``white light" cavity is to use some kind of dispersive medium. Two approaches to this are to use a negative dispersion material [42] (such as an atomic vapor) and to use a photorefractive crystal [43].

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

- Possibly, atomic clouds can be used as a form of squeezer in the SRC.
- It can slow down light, and possibly improve optical filters [40].

2.3.7.2 White-light cavity

Grating-based systems are shown to satisfy a rather general condition that $\partial\Phi/\partial\omega \geq 0$, which can also be connected with causality and conservation of probability [41]. The interaction with the atom system is to be determined.

2.3.7.3 Excess Noise

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 10^{-9} rad/$\sqrt{Hz}$ level.

2.3.8 Applications of Diffractive Gratings

Third generation.

2.3.8.1 All-reflective interferometers

Gratings can be used as beamsplitters in all-reflective interferometers [44]. These interferometers can potentially accommodate higher laser powers.

2.3.8.2 Alternative to multi-layer coatings

Gratings can be applied onto mirror surfaces to replace multi-layer dielectric gratings [45]

2.3.9 Significantly different configurations

For example, Displacement-Noise-Free Interferometry (DFI) [47]. Although DFI might turn out not to be suitable for ground-based detection, there might be new ideas in this vein.

2.3.10 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., [52]) 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?

2.4 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 1.

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

Appendices to Section 2, Advanced Interferometer Configurations

2.5 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.

2.5.1 Non-TEM modes

Three types of alternatives to fundamental TEM(0,0) modes have been considered, as summarized in table 2, also see the review article [48].

2.5.1.1 Higher Order Laguerre-Gauss Modes

The most straightforward 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 coverage 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 LG33 modes in a short cavity have also been carried out [9].

These modes are intrinsically degenerate – and therefore may cause complications when being attempted. 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?

2.5.1.2 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 [49].

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 [50]. For a pure m = 1, 2, 3 modes, explorations show that only slight improvements can be made [51].

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-spherical 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.

Mode	Mirror Shape	Coating Noise Suppression Factor, Amplitude	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 2: 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).

2.5.2 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).

2.5.3 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.

2.5.3.1 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, or with silicate bonding. 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 2nd generation suspensions.

2.5.3.2 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"?

2.6 Suspension Thermal Noise

The dominating noise source in the 10-40 Hz band would be the pendulum mode thermal noise of the monolithic fused silica suspension (c.f. **Error! Reference source not found.**). Around 12 Hz, the thermal noise of the bounce mode of the monolithic stage dominates.

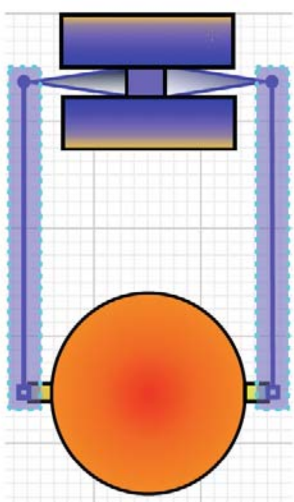
For the GWINC-based model used here to evaluate optical topologies, we have assumed an improved suspension configuration:

1. Cryogenically cooled (20K) Silicon fibers for the link between the PUM and test mass.

2. 4K Silicon blade springs at the PUM stage to reduce the vertical mode frequency.

This is clearly not a suspension design, but rather just a concept. It is likely that there will be major problems with trying to operate a suspension which such a large thermal gradient on its ears.

For more details and discussions, see Section 5.3



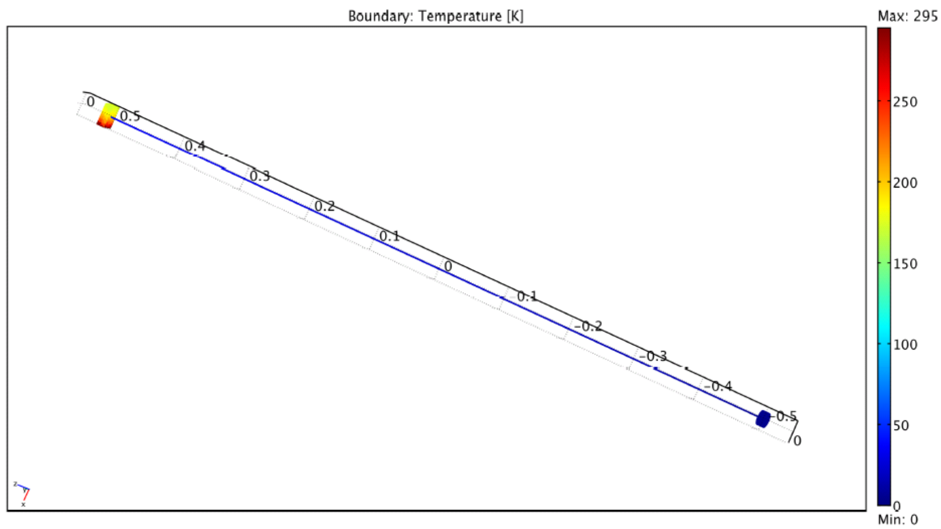


Figure 9: PUM cooled by conduction with 4K OFC copper braids. Si fiber cooled conductively via blades and radiatively by noncontacting radiative shield. Right: COMSOL model of fiber.

2.7 Straw-man configurations for LIGO2.5

In this section, we present two straw-man optical configurations for LIGO 2.5, 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 3 and plot their noise spectra in Figure 10.

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 3: Parameters assumed for Straw-man configurations

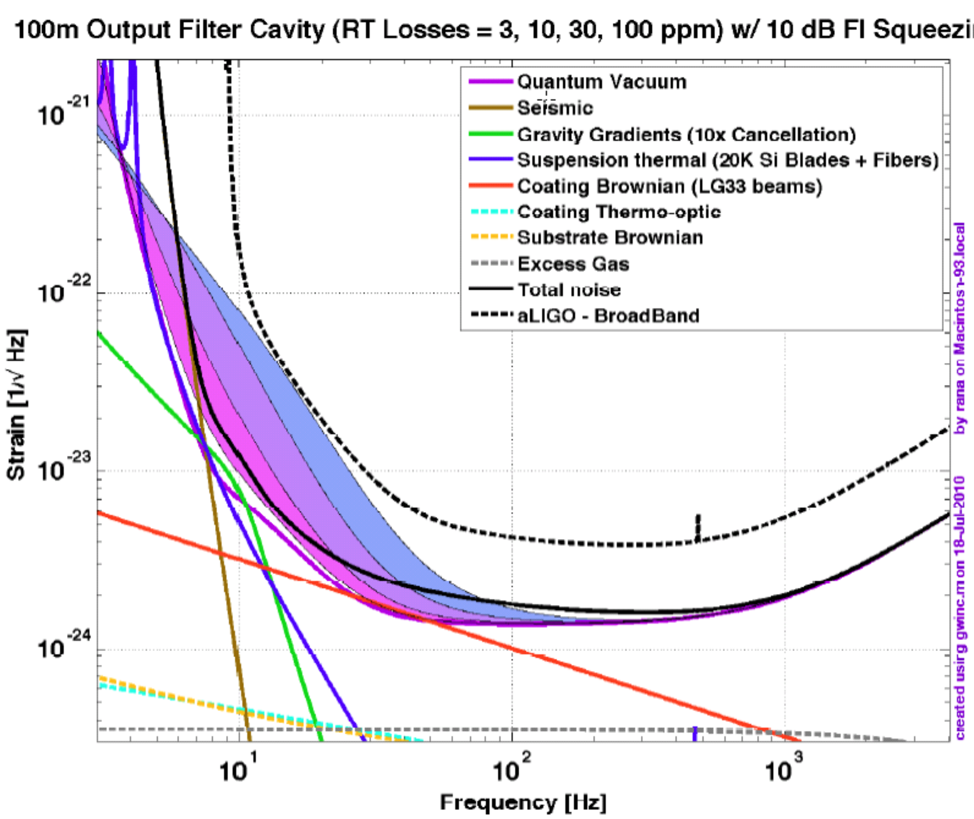


Figure 10: Noise spectrum using 10 dB of squeezing injection and a 100 m variational output filter cavity. The shaded regions indicate the low frequency quantum noise spectrum assuming round trip losses of 3, 10, 30, & 100 ppm in the output filter cavity.

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3 Light Sources

This working group addresses the lasers used to sense (or to help sense) the test mass position. With the progress in prepared light sources (squeezed light and squeezed vacuum) and their application, we have broadened the name of the group to 'Light Sources' to cover the scope of this Working Group. This provides a home for this research with its intimate relationship to the lasers.

3.1 Advanced LIGO Pre-Stabilized Laser - Background

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

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

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

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

3.2 Third Generation PSL

The laser sources required for third generation laser interferometric gravitational wave detectors depend strongly on the optical configuration chosen. All reflective interferometers have a much higher power handling capability than standard designs with transmissive optics. Sagnac-type interferometers need a laser source with low temporal coherence whereas layouts with optical cavities require a high frequency stability of the laser source. Coating thermal noise considerations might require a shorter wavelength of the laser light whereas interferometers with transmissive silicon optics require lasers with longer wavelength. The preferred spatial beam profile might not be a fundamental Gaussian distribution but rather close to a flat-top profile or a higher order Laguerre Gaussian mode. Even though thermal loading of the interferometer might limit the useful power level in the interferometer, an increase in the laser power might allow that one abandon the power recycling mirror. Most topologies would benefit of the injection of squeezed vacuum into the dark port of the interferometer.

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

3.2.1 High power concepts – Yb:YAG

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

3.2.2 High power concepts – slabs, rods

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

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

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

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

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

3.2.3 High power concepts – amplifiers

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

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

3.2.4 High power concepts – adaptive optics

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

3.2.5 High power concepts – alternative wavelengths

Laser sources at different wavelengths might be required for third generation detectors to reduce fundamental noise or to allow for different test-mass materials with better properties at either room temperature or cryogenic temperatures. Reducing the laser wavelength allows the reduction of the thickness of the coating layers and subsequently reduces coating thermal noise.

Increasing the wavelength to 1550 nm allows the use of silicon substrates as transmissive 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-Sa lasers could be chosen either at their fundamental wavelength (650 – 1070 nm) or in a frequency doubled layout. Frequency doubling or even tripling of high-power near-infrared lasers is a more promising option to provide a high power sources at shorter wavelength. An attractive approach is the external second-harmonic-generation (SHG)) in quasi-phase-matched ferroelectric materials such as MgO-doped periodically poled LiNbO_3 (MgO:PPLN), MgO-doped periodically poled stoichiometric LiTaO_3 (MgO:sPPLT) and periodically poled KTiOPO_4 (PPKTP). Green power levels of 16 W have been demonstrated by the conversion of a solid-state laser (Tovstonog et al. 2008) and almost 10 W were achieved in a SHG experiment using an infrared fiber laser (Samanta et al. 2009). Preliminary results at AEI indicate that resonant SHG in Lithium Triborate LiB_3O_5 allows power levels of more than 100W at 532nm to be achieved.

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 20W and higher power levels are expected in the near future.

As many different applications drive the laser development worldwide, many laser concepts at different wavelength and power levels are available. Depending on the requirements of third generation gravitational wave detectors one of these designs can be 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 1550nm light source with a power level of 50W.

3.2.6 Laser Stabilization

Power stabilization will probably be the most demanding laser stabilization task in future gravitational wave detectors. Technical power noise on the laser can couple via many paths into the gravitational wave channel as for example directly via a deviation from the dark fringe of indirectly due to asymmetric arms and radiation pressure noise. Advanced LIGO requires a relative intensity noise (RIN) of less than $2*10^{-9}$/rHz in the interferometer input beam to limit the motion of the test masses due to the time-varying laser beam force, and presumably future instruments will place even more stringent requirements. The accurate power noise sensing is difficult as the measurement can be contaminated by pointing, polarization, and potentially even frequency noise. Ongoing research is needed to understand these couplings.

3.2.7 Photodiodes

To get a quantum limited measurement of the power fluctuation of 500mW of light, new photodetectors need to be developed with sufficient power handling capability, spatial uniformity and quantum efficiency. First experiments showed that back- illuminated InGaAs diodes show promising features. However neither the spatial uniformity nor a sufficiently high quantum efficiency has been demonstrated so far.

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

3.3 Squeezed Light Sources

3.3.1 Squeezed light generation

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

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

Recently 12.5 dB of squeezing was produced with crystal systems. Work is required to convert such systems from the laboratory performance to a gravitational wave detector subsystem that can run well-controlled and reliably with a high duty factor. The 10 dB squeezing at the photodetection corresponds to a factor of 3.2 improvement in sensitivity. The LIGO facility limit is a factor of 10 below the minimum noise floor predicted for aLIGO. Given this and the loss of squeezing when coupled into an interferometer, development must focus on reliable squeezers generating significantly more than 10 dB of squeezing and good coupling to the interferometer.

Efforts to achieve large amounts of squeezing will require an understanding of the loss mechanisms in nonlinear materials (e.g. MgO:LN, stoichiometric MgO:LN PPKTP, PPSLT) to better inform improved methods for fabricating lower loss nonlinear crystals. This work is performed in conjunction with the Optics Working Group. One of the main loss mechanisms is the Faraday isolator used to inject the squeezed vacuum. Further reductions of the losses in Faraday isolators would improve the performance of squeezed light interferometer.

The term “ponderomotive” was introduced to describe the coupling between the amplitude and phase quadratures of a light field arising due to that field reflecting from a suspended, massive mirror. Radiation pressure moves the mirror changing the phase of the reflected light. In suitably configured interferometers the correlations so generated alter the form of the uncertainty relation generating squeezed states. Some advanced configurations use such a coupling induced internal to the main interferometer to beat the standard quantum limit (see AIC). Alternatively, it may be possible to use a separate suspended mirror system to generate large amounts of squeezing.

As the amount of squeezing increases, control of the squeeze angle becomes more and more critical, another path for research.

3.3.2 Squeezed light implementation

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

4 Optical Components

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

4.1 Research on Improving Advanced LIGO Optical Performance

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

4.1.1 Optical coating research

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

Doping the tantala layers with titania has been shown to reduce mechanical loss. Doping titania with silica also promises to improve Brownian thermal noise. Titania-doped tantala/silica has been selected for the Advanced LIGO coatings. 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. Both hafnia and niobia with silica, titania, alumina, etc as dopants are worth exploring as well. Hydrogen as a dopant has allowed for significant improvements in mechanical loss in silicon and may allow for improvements in other amorphous materials.

New treatments and designs, rather than materials, also 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.

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 shown that fused silica which is the glass known with lowest losses, has a substantially narrower Young's modulus spread than normal 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 Young's 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.

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

There has been progress in developing better theoretical models of thermal noise, given the experimental values of parameters like mechanical loss. The 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 not completely negligible effect. The effect of the finite size of mirrors, long overlooked or treated by numerical estimates, has been determined analytically. Theoretical efforts to look for correlations in different aspects of thermal noise, that could be tweaked to cancel out, are also underway. This effort has already stressed the importance of understanding the loss angle associated with shear modulus, which has not been measured directly by experiment but needs to be. Further modeling that includes a complete treatment of the temperature and mechanical strain dependence of the reflected light phase is still needed. In particular, this will include a proper treatment of stress-optic effects in the coating.

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.

Absorption of the interferometer circulating light in the coatings will result in thermo-elastic distortions of the optics and ultimately limit the circulating power. When coupled with the bulk absorption in the input test 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 on undoped tantala/silica coatings. Both the titania-doped tantala and silica-doped Titania coatings have been shown to have absorptions at or below 0.5 ppm. Any improvements beyond this level will make thermal compensation easier. 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 the Caltech-based Thermal Noise Interferometer (TNI; high displacement sensitivity interferometer testbed) can be used to set upper limits on thermo-optic noise in tantala/silica and titania-doped tantala/silica coatings, and additional mirrors for the TNI can be coated with any new coatings that show promise. Should results indicate that this thermo-optic noise will be a limiting noise source, it may be necessary to try to develop coating materials with improved dn/dT values. More complete understanding of thermorefractive noise is crucial when predicting the likely sensitivity of upgrades to Advanced LIGO and future detectors.

Concerns with scatter in 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 will be valuable to determine whether the problem is with the substrate polish or the coatings, whether new coating materials have the same or different coating properties, and whether the coating vendor affects the scatter. Detailed planning and development on clean handling and installation of the optics is important to keeping the scatter at the level set by the coating. This has relevance for near term Advanced LIGO procedures as well as for future instruments.

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

4.1.2 Fused silica test mass research

The OWG determined for Advanced LIGO that fused silica was the preferred test mass substrate material for that instrument. It is possible that reduced coating thermal noise (due to improved coatings and/or designs) could make thermal noise from silica substrates a significantly contributing noise source in an Advanced LIGO upgrade. Experiments are being conducted to measure mechanical loss in silica versus annealing parameters, including ramp down and dwell times. Annealing should not adversely affect the optical properties. Nevertheless, the optimized samples will be tested for increased absorption and scatter. Spatial absorption profiling will also be carried out to determine the observed level of substrate absorption inhomogeneity, necessary to understand to the level of thermal compensation that will be needed.

4.1.3 Thermal compensation research

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

To minimize the effects of these distortions the optic's temperature must be maintained more uniformly in the radial direction. One way this could be done would be to coat the barrel of the optic with a thin layer (a few microns) of a metal that reflects IR such as gold. Modeling indicates this would greatly reduce the radial temperature gradient in Advanced LIGO style test masses. Adding a gold barrel coating to the optics would have implication for other aspects of the design, notably thermal noise, charge mitigation, and parametric instabilities. Measurements of the mechanical loss of a thin gold coating indicate that the gold coating can be applied without adversely affecting thermal noise. It should be noted that any gold coating applied to the barrel for thermal compensation purposes will not reduce the optics modal Q's enough to cause significant improvement in parametric instability performance. Tests of a gold coatings interaction with possible charge mitigation schemes, including UV, are underway. Results of these tests might require follow-ups with other materials and/or coating methods or with additional modeling. While Advanced LIGO has decided not to make this part of the baseline design, the technique may be interesting 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. This will require research on carbon dioxide lasers, to reduce noise and possibly boost power, and potentially on measurement and control issues. In addition, by moving to shorter wavelengths it might be possible to develop MEMS or other technology based spatial light modulators to allow a programmable heating beam profile.

4.1.4 High power effects in Advanced LIGO

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

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

4.1.5 Modeling thermal effects in Advanced LIGO

The development of realistic models of the performance of the interferometers is also crucial to achieving the performance goals of Advanced LIGO and its upgrades. Efforts are focused on the SIS (Static Interferometer Simulation) model, using FFT-based Huygen's principle light propagation, for investigating how the interferometers will perform when operating at full power.

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

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

4.1.6 Diagnostics for Advanced LIGO optics

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

4.1.7 High power optical components

Electro-optical modulators and Faraday isolators are essential parts of every interferometric gravitational wave detector. Apart from the laser gain medium, they are the components which experience the highest power densities in transmission in the entire interferometer. RTP based electro-optical modulators have been developed and tested for Advanced LIGO. Similarly, Faraday isolators with internal compensation schemes to reduce thermally driven depolarization and beam quality degradation have been developed and tested for Advanced LIGO.

A thermal compensation system for Advanced LIGO input optics is being developed and tested at the University of Florida. This is for risk reduction in Advanced LIGO as it is not expected that the baseline design will require input optic thermal compensation. This system uses four electrical heaters in thermal contact with input optic elements and is capable of controlling both symmetric and astigmatic aberrations *in situ*.

Advanced LIGO upgrades might need even more laser power to increase its high frequency sensitivity or reduce the need for power recycling. Future detectors might operate at a shorter wavelength to reduce coating thermal noise or use a longer wavelength to take advantage of silicon. Any of these changes requires a targeted research program to identify the best optical materials and to develop sufficient compensation techniques to eliminate thermal lensing and laser power induced birefringence and optical damage in these essential components.

4.1.8 Charging of test masses

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

Shining UV light on *in situ* optics is being investigated as a way to mitigate charge buildup. This involves testing UV LEDs, developing AC driver electronics, and doing experiments to determine if the UV can cause harm to the optics or their coatings. Coated optics are tested by subjecting them to UV light for days to weeks at a time, then are re-measured for optical absorption and mechanical loss. Results on tantala/silica optics indicate that UV can cause increased optical absorption but the levels of UV exposure needed for charge mitigation will likely not harm the optics. Follow-up work is in progress using titania doped tantala/silica coatings as well as on whether different cleaning and handling techniques influence the effect of UV on the optics and their coatings. Experimental work on low energy 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.

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.

This work is performed in conjunction with the Suspensions Working Group.

4.1.9 Variable reflectivity signal recycling mirror

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

4.1.10 Investigation into sources of non-Gaussian noise

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

4.2 Optics Research and Development for Third Generation Detectors

The OWG also conducts directed research for future gravitational wave detectors beyond Advanced LIGO. While this research is more speculative and long term than that directed toward 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.

4.2.1 Beam Shaping

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

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

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

4.2.2 Development and characterization of novel optical materials

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

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

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

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

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

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

4.2.3 Cryogenic Mirror Coatings

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

Mechanical loss measurements of coating materials at low temperature are also a valuable way to explore the microscopic causes of internal friction. Identification of Debye loss peaks allows for association of mechanical loss with particular molecular motions, like bond stretching or bending.

This understanding, coupled with theoretical and modeling work on coating mechanical loss, is becoming very important to the effort to reduce coating thermal noise in future detectors.

4.2.4 Directed Radiative Cooling

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

4.2.5 High efficiency grating development and characterization

All-reflective interferometers using diffraction gratings as optics avoid problems associated with the transmission of large laser powers through optical substrates. High finesse optical cavities have been demonstrated using small gratings. The challenge will be to scale up the optical aperture to what is required for a large detector. In addition, absorption by the grating surface 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. This work is performed in conjunction with the Advanced Interferometer Configurations Working Group.

4.2.6 Low loss nonlinear optical materials for squeezed light interferometry

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

4.2.7 Composite masses

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

4.2.8 Shorter Wavelength Light

One way to reduce coating thermal noise is to simply make the coatings thinner. This naturally occurs if a shorter wavelength of light is used in the interferometer. With upconversion efficiency, it may be possible to produce green light directly from the Advanced LIGO 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 Light Sources Working Group.

4.2.9 Coating-less or coating-reduced optics

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

5 Suspensions and Isolation

5.1 Introduction

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

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

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

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

Most of the R&D for all the Advanced LIGO isolation and suspension sub-systems is well underway and final designs have been chosen. There is still some ongoing R&D of immediate relevance to Advanced LIGO, which will serve to reduce commissioning time or may prove to be of use in enhancing aspects of the performance of the currently conceived Advanced LIGO designs. This work is discussed in section 5.2. However we are now moving into a period of increased focus on conceptual designs and laboratory research for future, more advanced detectors. The technology development toward 3rd generation detectors is discussed in section 5.3.

5.2 R&D to support Advanced LIGO commissioning and upgrades

5.2.1 Isolation systems

5.2.1.1 Current status and ongoing work

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

5.2.1.2 Tilt/horizontal coupling and advanced seismometers

One of the limits to the performance of seismic isolation systems is the coupling between ground tilt and horizontal motion of the isolation platforms. This is fundamentally caused by the inability of a horizontal sensor (or a passive horizontal isolation stage) to distinguish between horizontal accelerations and tilts in a gravitational field. This tilt-horizontal coupling causes a variety of problems at the microseismic peak (~0.16 Hz), and is a basic limit to the performance of the systems at these frequencies. The Advanced LIGO test-mass isolator prototype is now limited by this coupling at low frequencies, and an external sensor could be easily integrated into the system to reduce amplification of low frequency noise. The performance limitation increases the amount of control needed at the pendulum, and complicates lock acquisition. Several methods of addressing tilt issues are being pursued. 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. Firstly one can use pairs of differential vertical seismometers, whose spatial separation would allow us to measure ground tilt. Secondly a suspended bar tiltmeter is undergoing preliminary tests and will also yield results on losses in different materials. Thirdly 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. Development of tiltmeters is an area in which collaboration with Virgo colleagues is also underway.

5.2.1.3 Suspension point interferometer

It is also possible to improve the performance below 1 Hz with an auxiliary system which reduces the differential motion and tilt of the various optical tables in the detector. This type of approach has been discussed for many years, and is traditionally called a 'Suspension Point Interferometer' (SPI), i.e., an interferometric sensor which measures between the points which suspends the arm mirrors. The system we are investigating is slightly different; we plan to control the relative motion of the optical tables, which is why this system is called the Seismic Platform Interferometer. The relative motion of the tables for this system will need to be measured in at least 3 degrees of freedom, namely length, pitch, and yaw. This will allow the detectors to be mounted securely to the table, and will also allow the benefits to be shared by multiple suspensions on the same table, a common situation on the HAM optical tables. The systems impact of this approach is reflected in its presence also in the Configurations Working Group thinking.

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

5.2.2 Suspensions

5.2.2.1 Excess thermal noise from clamps and break-offs

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

5.2.2.2 Multiple pendulum suspensions - mechanical and control aspects

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

5.2.2.3 Development of monolithic final stage

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

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

Further understanding and characterizing of losses in silica fibres including investigations of non-linear thermoelastic noise and of surface losses could lead to improvements for possible application to upgrades to Advanced LIGO. An increase in strength could allow reduction in cross-section and in vertical bounce frequency, enhancing isolation. *See also 5.2.2.6.*

5.2.2.4 Violin mode damping

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

5.2.2.5 Creep 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 fibres has been carried out with no non-thermal noise being seen at modest sensitivity (insufficient to exclude it as a significant noise source for aLIGO). Work has been done to study the noise associated with the violin modes of the silica suspensions in GEO 600 and further work is underway to extend these studies by modeling to put upper limits on the expected noise in Advanced LIGO. No work as yet has addressed transients coming from higher up the suspensions and/or from the silicate bonded test-mass ears. Direct experiments to characterise the level of and/or put upper limits at a meaningful sensitivity level to potential non-Gaussian transient events associated with the Advanced LIGO suspension system are challenging. However new ideas for carrying out such experiments are encouraged.

One approach which will be pursued to observe the impulsive releases of energy or acoustic emissions ("creak effect") is to strain the element statically while also driving the element through a large amplitude motion at low frequency below the measurement band, while interferometrically measuring the element at high sensitivity in band (above 10 Hz). By large amplitude motion we mean much larger (100-1000 times) than the out of band motions estimated through modeling. 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. In addition to the very large motions we should be able to directly look for noise in the UIM and PUM stages at nominal levels - we only have to be able to measure noise levels of $\sim 10^{-16}$ m.

5.2.2.6 Low noise cantilever blade springs and improved suspension thermal noise

Glassy metal and ceramic blades could be considered as a replacement for maraging steel in the upper stages of the test mass suspensions to reduce fractal noise if that is shown to be a problem, see 5.2.2.7. 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. 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.

5.2.2.7 Low Frequency Noise

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

5.2.2.8 Control aspects and different payloads

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

5.2.2.9 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. The current design of the aLIGO quad suspension has 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. However for any future enhancements we will need to consider further changes, for example to the geometry of the reaction mass to increase the gap except where the ESD coating is present. For 3rd generation detectors new methods for the mplementation of controls for global actuation will need to be developed to reduce gas damping effects further.

5.3 R&D Towards Third Generation Detectors

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

a) reductions in suspension thermal noise

b) improved seismic isolation

c) reduction of ‘Newtonian’ or ‘gravity gradient’ noise

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

5.3.1 3rd Generation Isolation systems

5.3.1.1 Very low frequency passive isolation

An alternative approach to isolation, using very low frequency passive isolation, has seen application in e.g., Virgo and TAMA. Elements of this approach may be applicable to 3rd generation instruments as an effective extension of the pendulum suspension isolation, especially for cryogenic instruments where managing the thermal conductivity of the isolation system is important. The R&D on the passive system to date has improved our understanding of mechanical systems significantly and has led to the discovery of an additional mechanical noise mechanism (see 5.2.2.7), which needs to be studied for future lower frequency observatories, and possibly to fully understand the low frequency noise of Advanced interferometers. An isolator based on the this design is being developed for the 10m Hannover test facility, and is being considered for injection detection benches in Advanced Virgo.

5.3.1.2 Newtonian coupling

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

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

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

5.3.1.2.1 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:

- 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.
- 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.

5.3.1.2.2 Underground

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

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

- Continue developing the array of underground seismic stations at the Homestake mine (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.

5.3.2 3rd Generation Suspensions

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

5.3.2.1 Silicon suspensions

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

5.3.2.2 Attachment techniques

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

5.3.2.3 Larger masses

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

5.3.2.4 Cryogenics – suspension and isolation aspects

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

5.3.2.5 Cryogenics – radiative cooling

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

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

5.3.2.6 Magnetically Assisted Suspensions

An alternative approach to achieving suppression of seismic noise at low frequencies is to develop magnetically assisted suspensions. The basic idea here is to use magnetic or RF field 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 > 6m long pendula). 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.