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LSC White Paper on Detector Research and Development

1 SUMMARY AND INTRODUCTION

The document presents a recommended program of research and development for the Laser Interferometer Gravitational-wave Observatory (LIGO). The program is the result of deliberations of the three technical development groups of the LIGO Scientific Collaboration (LSC). The subject of the groups are:

- Reduction of stochastic forces - isolation and suspension systems (Chair, David Shoemaker)

- Reduction of sensing noise - lasers and optics (Chair, Eric Gustafson)

- Interferometer configurations (Chair, Kenneth Strain)

A companion document presenting the LSC recommended program in detector characterization and data analysis will become available in the fall of 1999.

The guiding considerations in designing the research and development program have been:

- broadening the detector’s sensitive band by reducing the limiting noise terms,
- the reduction of the noise in the spectral region of maximum sensitivity around 100Hz,
- the assessment of the technical maturity and feasibility of the improvement,
- the increase in detection range of posited astrophysical sources.
- the need to maintain both a near term development program and a long range basic research effort to exploit the capabilities of the LIGO facilities.

The principal assumptions made in formulating the research and development program are:

- no detection has been made to guide the research past the current best guess strategy,
- changes in the initial LIGO detector will be introduced in such a manner that one interferometer is always operating,
- the first changes will be made after a two year observing period with the initial LIGO detector,
- an element in the strategy for incorporating the improvements in the detector is to minimize the loss in observing time and to anticipate future improvements.

The anticipated improvement in the detector performance as a result of the recommended research program is indicated in Figure 1 with the parameters listed in Table 1. The various elements of the program are outlined in Table 2 and a preliminary schedule for the development leading to incorporation in the LIGO is given Table 3.

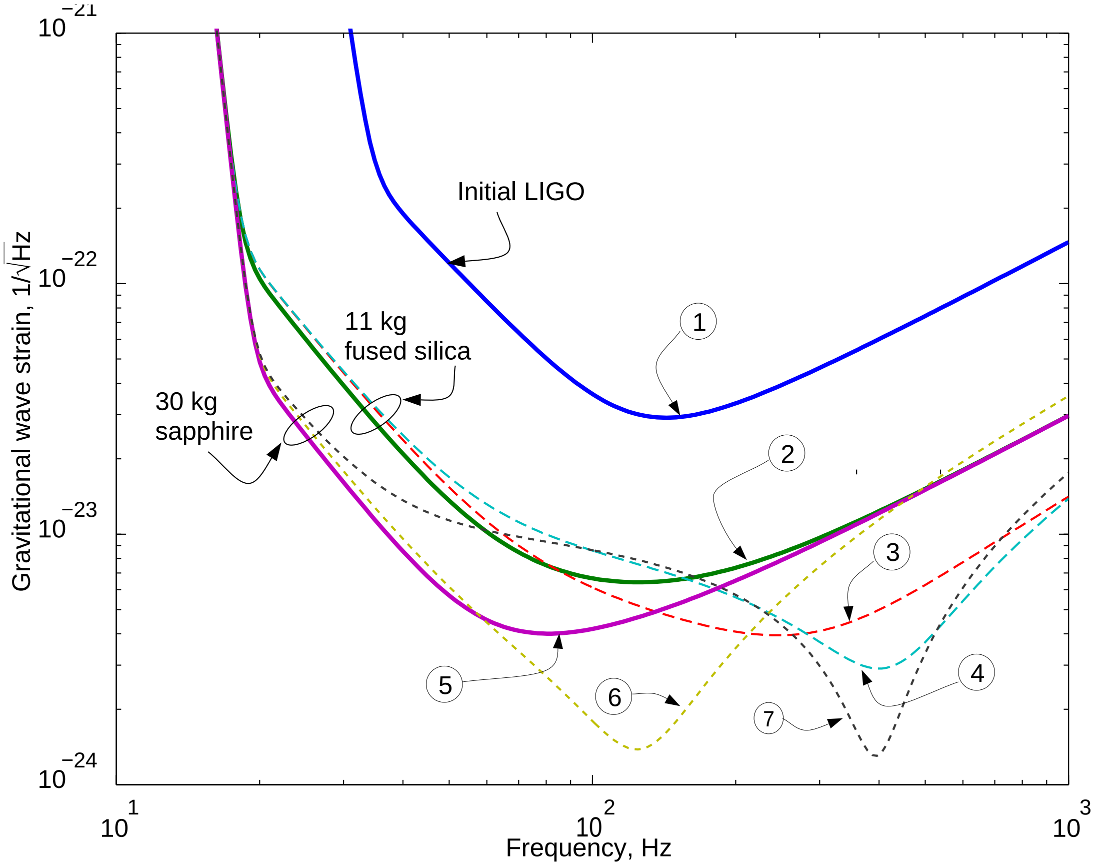
The program is divided into three components: LIGO II near-term, LIGO II medium-term and LIGO III. The LIGO II near term changes are contemplated for incorporation in the LIGO by the end of 2004. They make significant improvements in the LIGO sensitivity based on the engineering development of existing technology or modest stretches from present day systems. Several of the near term improvements must be made to gain the full advantage of subsequent steps. The goals of the medium term program are more ambitious technically but considered possible for incorporation in LIGO by the end of 2006. The elements of the LIGO III program comprise a basic research program to develop technology and techniques to improve the sensitivity and bandwidth of the LIGO to the limits imposed by the facilities or to the fundamental limits of the metrology. It is not possible to divine the “correct” approach to several of the major goals of the long range program so that several different promising directions to attain similar ends are recommended. These programs need to be carried to a point where it is possible to make an informed decision on continued development.

The program is illustrated in Figure 1 and the accompanying table. Curve 1 is the performance of the initial LIGO interferometer. At low frequencies (<40 Hz) it is dominated by seismic noise; from 40 to 150 Hz it is dominated by thermal noise (Brownian motion of the test masses), and at frequencies greater than150 Hz the dominant noise source is photon shot noise (the limit to precision given by counting statistics).

The LIGO II near-term improvements to the interferometer in the planned program are shown in curve 2. Significant reductions to the thermal noise are made by introducing fused silica fibers in the test mass suspension, simplifying the attachment to the test mass and moving actuation away from the test mass. Moderate improvements in the seismic isolation move this ‘wall’ down below the new thermal noise floor. An increase in the raw laser power to ~100 watts, with consequent changes to the input optics, delivers roughly 10 times more power to the interferometer. To reduce resulting thermal lensing, lower absorption substrates are used for the test masses and in addition a compensation of the laser-beam induced lensing is added. This configuration approaches the Standard Quantum Limit (SQL) for a 10 kg mass around 100 Hz, where the stochastic radiation pressure and the shot-noise limited readout are close to dominating the sensitivity.

Signal recycling is added for the LIGO II medium-term improvements. This shapes the shot-noise limited response of the interferometer, allowing either a broad-band redistribution of sensitivity to better match the underlying thermal-noise limit (curve 3) or selection of a narrow frequency band to focus on a particular gravitational-wave signal (curve 4). This improvement requires the addition of one mirror to the interferometer and changes in the control system.

Also shown is the impact of a change in the test masses from fused silica to sapphire (representative of several possible materials). The higher density and lower mechanical loss of sapphire should result in a significant reduction in the thermal noise and less motion due to the random radiation pressure, leading to quantum-limited performance for the 30 kg mass. For an optical configuration like LIGO 1, the sensitivity follows curve 5; with signal recycling, possible responses are shown in curve 6 and 7. These changes require significant advances in materials technology and so are considered possible but ambitious for LIGO II.



Parameter	Curve 1	Curve 2	Curve 3, 4	Curve 5, 6, 7
Parameter	Initial LIGO I value	Double suspension, 100 W laser, thermal de-lensing	Signal tuned configuration	Alternative test mass material
Input power to recycling mirror	6w	62w	140w	
Mirror loss (transmission+scatter)	50 ppm	20 ppm		
Effective power recycling	30	93		
Substrate absorption	5ppm/cm	0.4 ppm/cm		17 ppm/ cm
Thermal lensing correction	(none)	factor 10		
Suspension fiber	steel wire, $Q = 1.6\times10^{5}$	fused silica $Q = 3 \text{ x } 10^{7}$		
Test mass	fused silica, 10.8 kg, $Q = 1\times10^{6}$	fused silica, 10.8 kg, $Q = 3\times10^{7}$		sapphire, 30 kg, $Q = 2\times10^{8}$
Signal recycling mirror transmission	(none)		T=0.6 (curve 3) T=0.15 (curve 4)	Curve 5: none T=0.3 (curve 6) T=0.09 (curve 7)
Tuning phase			0.7 rad (curve 3) 0.45 rad (curve 4)	1.3 rad (curve 6) 0.45 rad (curve 7)

Figure and Table 1 : Performance and parameters of interferometers described in program.

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	Top-level Goal	Key technologies
LIGO-II **near-term** research results	• factor 6 increase in distance of detectable NS binaries • SQL 11 kg test mass	• 100 W laser source to reduce shot noise and ancillary optics • correction of thermal lensing to permit higher powers • use of low-absorption optical substrates to permit higher powers • Double pendulum test mass suspension with silica substrate and lower pendulum fiber to reduce thermal noise • elimination of all actuation on the test mass to reduce thermal and excess noise • Active low-frequency isolator to reduce RMS motion
LIGO-II **medium-term** research results	• additional 3x increase in NS binary seeing • SQL 30 kg test mass	• incremental increases in laser power • signal-tuned interferometer configuration to reshape the shot-noise limited sensitivity • lowered coating absorption • larger test mass (~30 kg) to reduce radiation pressure noise; alternative test mass material to lower thermal noise for end test masses • improved isolation via active and/or passive systems to realize benefit of lower thermal noise
LIGO-III research targets	• further 5x increase in NS binary seeing • Performance limited by facilities down to 15 Hz • SQL 300 kg test mass • Performance exceeding naive facility and quantum limits	• megawatts of circulating power to reduce shot noise • alternative test mass materials for optical, thermal, and mechanical properties • Cryogenic test mass and suspension *and/or* sensing/feedback to significantly reduce thermal noise • larger test mass to reduce radiation pressure noise • additional active or passive lower-frequency isolation, probably requiring additional auxiliary sensor/actuator layers to realize benefit of lower thermal noise • extra low-frequency isolation for detection down to gravity gradient noise, perhaps below. • alternative optical configurations • QND readout scheme with low circulating power

Table 2: Research and Development Program for LIGO-II and LIGO-III systems

Table 2 summarizes the program. The left-hand column shows the time scale for the implementation (2004 for near-term LIGO II, 2006 for medium-term LIGO II, and ~2008 and beyond for the LIGO III targets). The top-level goals (the relative distance to which neutron-star (NS) binary inspiral events can be observed, standard quantum limited mass) are shown in the second column; the third column indicates the key technologies which would enable these goals. The program is described fully in the sections which follow.

	Double pendulum suspension	100 W Laser and ancillary optics	Signal-tuned Configuration
Top-level Requirements review	4th qtr ‘98	1st qtr ‘99	2nd qtr ‘99
Conceptual design; **Design summit**	1st qtr ‘99	3rd qtr ‘99	1st qtr ‘00
Internal requirements, component research, configuration trades; **Preliminary Design Review**	2nd qtr ‘99	1st qtr ‘00	3rd qtr ‘00
Component Prototypes; **Test Review**	3rd qtr ‘00	1st qtr ‘01	4th qtr ‘02
Fabrication of Engineering Prototypes	1st qtr ‘01	1st qtr ‘02	4th qtr ‘04
System tests; **Final Design Review**	3rd qtr ‘02	1st qtr ‘03	1st qtr ‘05
Fabrication complete	4th qtr ‘03	4th qtr ‘03	3rd qtr ‘05
Installation complete	2rd qtr ‘04	2nd qtr ‘04	1st qtr ‘06
Shakedown; **Commissioning**	4th qtr ‘04	4th qtr ‘04	3rd qtr ‘06

Table 3: Schedule for LIGO II improvements (end dates)

Table 3 gives rough schedules for the near-term improvements. Estimates for the later stages (fabrication, installation, commissioning) were made based on LIGO I plans and experience.

2 THE LIGO II CONFIGURATIONS PROGRAM

2.1 The LIGO II near term configurations program

Signal recycling allows the frequency response of the interferometer to be adapted to match anticipated signal spectra, rather than having peak response at zero signal frequency. A very important additional benefit is `closure' of the output port of the interferometer by the signal recycling mirror. This enables an improvement of the contrast, hence power build up, and sensitivity of an interferometer that is limited by many classes of optical defect (including thermal effects). It can also improve the efficiency of transfer of modulation sidebands used for control of the interferometer.

The configurations program for LIGO II is concentrated on the development of signal recycling techniques (dual recycling or resonant sideband extraction) to produce a signal-tuned interferometer. To prepare for this stage the Advanced Interferometer Configuration Group (AIC) will work to optimize the core optical system within the context of the near term program. This will take into account the possibility of later addition of signal recycling as described below, to allow for a delayed or progressive implementation of the medium term configuration.

Optimization of the near term LIGO II optical system consists of choosing suitable finesse for the arm cavities and also the power recycling factor. A solution will be found that provides good performance whether or not the signal recycling is implemented. This allows later addition of signal recycling at minimum cost.

2.2 The LIGO II medium term configurations program

Due to the complexity of the change to signal recycling (dual recycling (DR) or resonant sideband extraction (RSE)), it is considered necessary to undertake a series of suspended-mass prototype experiments, in conjunction with computer modeling. These will test sensing and control systems, efficiency of read-out systems and correct handling of optical distortions. The single most important aspect of such tests will, however, be studies of lock acquisition in signal recycling systems.

To allow a smooth transition from prototyping through development and implementation on LIGO interferometers, the prototyping program will be closely integrated and have significant input from the LIGO Laboratory.

Initial work is needed to find the optimum signal recycling configuration to obtain the frequency response and sensitivity for LIGO. The complex problem of finding a suitable control system for signal recycling will be tackled by a combination of numerical modeling and experiment. Groups at LIGO/Caltech, UF, ACIGA/ANU and GEO are undertaking, or have completed, bench-top tests and modeling to allow a locking scheme to be found and studied. The orthogonality of control signals for all degrees of freedom (signal matrix) and the signal to noise ratio (purity) of these detector outputs will be investigated. The Software Tools for Advanced Interferometer Configurations (STAIC) meetings will continue to focus on the simulation of DR/RSE systems. These meetings will be a forum for the development of control systems for LIGO configurations, work that will be closely coordinated by the AIC.

2.3 The LIGO III program

Development of DR/RSE will be continued to allow optimum use of incremental improvements in optical performance due to better coatings higher thermal conductivity substrates and also more aggressive active thermal correction. Further improvement in sensitivity to a variety of signals can be obtained by adaptively tuning the interferometer to keep the peak sensitivity at the frequency where most of the signal power is to be found. This can be achieved by using on-line data analysis to select the best tuning frequency for DR/RSE. This work will be carried out after the medium term goals have been satisfied.

Sagnac interferometers could provide an alternative approach to reducing the photon shot noise, and this is the only new classical configuration that has been selected for further study. To push beyond the limits imposed by classical interferometry, however, quantum techniques represent the only way forward. Since even the minimum performance envisaged for LIGO III is close to the standard quantum limit (SQL) for massive mirrors, these techniques may be required at a relatively early stage and should be developed urgently.

2.4 The Sagnac interferometers program

The Sagnac interferometer is being considered as part of a systems approach where a high powered broadband laser is used with a delay line Sagnac. This will simplify the control of the interferometer and allow the use of opaque core optics. Such materials can have more favorable thermal properties than existing transparent substrates. Before moving away from conventional interferometer configurations considerable work at the table top level combined with computer modeling and a prototype with suspended optics will be required.

The research will be carried out at Stanford. Experiments in thermal loading will be carried out by 6/00; and a broad-band laser source will be implemented by 12/00.

2.5 Interferometry using squeezed light

Squeezed light can enhance the performance of an interferometer that is limited by photon shot noise. Interferometry experiments have demonstrated an improvement in SNR by a factor of 2 using squeezed vacuum states. The problem with this technique is that squeezed states are very fragile and easily destroyed by optical losses. New results predict that squeezing is compatible with dual recycling, and, depending on the conditions, an improvement in sensitivity, or an increase in interferometer bandwidth, can be obtained.

Research in squeezing applied to interferometry will be carried out at ACIGA/ANU until 2008.

2.6 QND Configurations

The Standard Quantum Limit (SQL) -- which is produced by the combination of shot noise and radiation-pressure noise -- can be circumvented, in principle, by Quantum Non-demolition (QND) techniques.

LIGO II, in 2004, will likely be close to the SQL at the minimum of its noise curve. Thereafter, any further lowering of the noise minimum will require increasing the test masses upward from 11 kg (an increase that cannot continue for long because of practical constraints), and/or implementing QND. Thus, QND may be useful in LIGO as early as 2008. Given this time frame, it is important to invent a practical scheme for QND in the next one or two years and then embark on laboratory development of the necessary techniques and on prototyping.

Recent theoretical analyses by the MSU group have produced several promising ideas that may lead to a practical QND configuration for LIGO. These include schemes for (1) using light pressure to transfer the gravitational-wave signal to a small readout test mass, (2) putting that signal into QND observables (observables that can circumvent the SQL) such as the readout mass’s momentum, and (3) measuring the relevant QND observable (including a momentum-measuring readout system called a “speed meter”).

Configurations based on these ideas appear capable of broad-band QND measurements, and of operating at much lower laser power than conventional configurations. However, as yet no practical conceptual configuration has been found that will achieve both these features simultaneously.

Table 4: Tasks, Coordinators, Active Groups

Selection/Optimization (Fritschel)	LIGO/MIT, LIGO/Caltech, UF, GEO
Dual Recycling/Resonant Sideband Extraction (Strain)	ACIGA/ANU, GEO, LIGO/Caltech, UF
Sagnac Interferometers (Fejer)	Stanford
Squeezing (McClelland)	ACIGA/ANU
QND (Braginsky)	MSU, CaRT

3 SUSPENSIONS AND ISOLATION SYSTEMS

3.1 Overview

Our effort is highly structured for the first upgrade to LIGO (referred to as LIGO II), but we are exploring promising solutions with a longer perspective (‘LIGO III’) which will evolve as our understanding of the requirements and the technical paths improve. The LIGO III (or ‘Advanced Interferometer’) performance target (as discussed in the introduction) requires significant steps forward in all domains of the suspension, isolation, thermal noise, and the relevant control issues. Our present goal is to ensure that long-lead technologies with a significant probability of success are set into motion now. In addition, whenever possible, we choose solutions which are both applicable in the near-term and (with evolution) in the far-term.

We have organized our group so as to arrive at a useful design for LIGO II in a timely way. Individuals in bold type in Table 5 will organize the designated subsets of the research program; note that efforts are often collaborations between members of different groups. The Working Group Coordinator (Shoemaker) is charged with managing the overall suspension design process, and with crafting a decision on the final design. We will follow the documentation and review procedures used successfully in the LIGO I design. These structures will help ensure that the LSC will form and execute a coherent design.

3.2 Baseline Assumptions for LIGO II

We start with the boundary conditions for our design; these are driven by the assumptions outlined in the executive summary for the mid-decade upgrade.

1. The suspension improvements will be directed principally at the components suspended from the vibration isolation stack, but will not involve replacing the initial LIGO stack itself. Modifications to improve performance can be considered.
2. Fused silica will be the best material available for suspension fibers; test masses may be fused silica (using presently available technology) or sapphire or other promising crystals when they are ready.
3. The present 11 kg, 25cm diameter test mass remains the baseline dimension. Test masses of up to 30 kg will be accommodated, via larger fused silica masses or higher density material, if available.

3.3 Strawman LIGO II System

Ever since the decision was made to use a single pendulum in the LIGO I interferometer, it has been envisioned that an early upgrade would replace it with a multiple pendulum configuration. We have received tremendous benefit from the experience of our colleagues working on other projects, especially the work of our GEO colleagues (who are also members of the Suspension Working Group) on developing the suspension design for the GEO 600 interferometer. The debt we owe to this work should be obvious below, but is specifically acknowledged here.

There are several clear advantages to a double pendulum. Perhaps the most important is to provide a location to apply control forces for locating and aiming the test mass that is isolated from the test mass itself. This has several benefits: 1) it provides a mechanical filter to reduce noise injected by the controllers and the thermal noise of the lower Q isolation stages above, and 2) it enables us to reduce greatly (or eliminate) all control forces exerted on the test mass itself. The latter feature will allow the elimination of the magnets attached to the test mass in LIGO I (which are the largest source of excess dissipation on the test mass), and should allow the test mass to reach a Q limited principally by the substrate material. Thus both technical noise and fundamental thermal noise are anticipated to be substantially reduced in such a suspension.

Adding another pendulum stage also improves the seismic isolation of the test mass for horizontal excitation of the pendulum support point; this is a valuable feature, but requires augmentation with vertical isolation to be effective. Vertical seismic noise can enter the noise budget through a variety of cross-coupling mechanisms, and simple pendulums are much poorer vertical isolators than most other isolation stages (having resonant frequencies no lower than ~15 Hz). Thus, another key feature of a new suspension needs to be provision of additional vertical isolation.

We will use the GEO 600 design as a starting point. The main relevant features of its design include a triple pendulum whose upper stages are used for control purposes and for vertical compliance; all-fused-silica construction in which the fused silica test masses are suspended from fused silica fibers (or perhaps ribbons), which are attached using the silicate bonding technique developed at Stanford; sufficient rigidity in the suspension of the test mass (such as the use of 4 fibers) to allow all alignment degrees of freedom to be controlled from the upper masses; use of magnets for control on upper stage(s), but no magnets on the test mass itself (either electrostatic actuation and/or photon pressure will be used on the test mass); and an active pre-isolation system for reduction of micro-seismic noise (as discussed below).

We add, for the LIGO II design goals, flexibility in the test mass material, the possibility of high-gain active isolation both inside and outside the vacuum, and a specific goal of eliminating all actuation on the test mass.

3.4 Baseline Assumptions and Strawman for LIGO III

Both the target performance and the means to achieve it are considerably less well defined for the significant advances needed for LIGO III. Nonetheless, we intend to strive for a sensitivity approaching the facilities and fundamental limits. This leads to the following targets for the suspensions/isolation design:

- seismic noise will be limited to the gravity gradient limit for frequencies higher than 15 Hz
- suspension thermal noise will be reduced to be comparable to the SQL for a 300 kg test mass
- internal thermal noise will be reduced to be comparable to the best case residual gas fluctuations

The technologies and concepts we feel need exploration now are indicated in the text in the appropriate subsection. Briefly, they are:

- cooling of suspension and/or test masses to reduce the noise temperature and to take advan-

tage of material loss dependence on temperature
- materials research to enable the above; alternative test mass materials, suspension fibers and alternatives to fibers, and ways to interface those materials
- sensing and high-gain feedback for the thermally-driven suspension fiber modes and possibly the internal test mass modes
- a mix of passive and in-band ('high gain') active seismic isolation; development of seismometers of requisite sensitivity
- accommodation of the significantly larger (mass, size) test mass

3.5 Design Requirements and Trade Studies

The design process will start from the suppositions described above. Additional inputs to the design will come from the research programs, described below. Guiding the process will be a formal set of design requirements, and trade studies aimed at identifying specific designs that can meet the requirements. We intend to model the process after the successful LIGO subsystems approach, where documentation, reviews, and milestones help keep the undertaking focussed and well interfaced to other developments for LIGO. We intend to arrive at a single complete design through this process, with the coordinator developing the consensus.

Once the requirements are established, we will evaluate a variety of candidate designs (with specificity that increases with time) to determine the best way to meet the requirements. This is an iterative process, and since it involves design synthesis can not be a purely mechanical procedure that can be completely prescribed in advance. Nevertheless, the sorts of the design questions that are likely to arise in the first few passes through the process are clear. We will endeavor to adopt solutions which have relevance for both LIGO II and more advanced interferometers and which have design flexibility to allow incorporation of advances as they become available.

The starting point is a multiple pendulum scheme based on the GEO 600 suspension, and GEO will lead the trade studies. Within that framework, there are a number of specific questions to address, including:

- number of stages and their masses and dimensions,
- wires or ribbons, number of them, dimensions, means of fabrication, and attachment,
- necessity of reaction masses, and designs of this system if required,
- sensing and actuation systems, including whether we can construct a system without any direct actuation on the test mass,
- mix of reliance on passive and active isolation.

3.6 Controls research

The design process needs to confront the performance goals with a variety of techniques from control engineering. Achieving the LIGO II performance goals is closely linked with our ability to reallocate control authority away from the test mass.

Seismic excitation in the ‘control band’ (roughly 20 Hz and lower) dominates the RMS excursion (both displacement and velocity are of importance) of the test masses, and thus defines the requirement on actuator authority. Reducing the control authority necessary on or near the test mass will allow us to eliminate actuators which increase thermal and excess noise in the test mass. Proper design should also improve interferometer availability by improving the robustness of the fringe locking servo and the rapidity of lock acquisition.

Control functions to be pursued include

- re-allocation of control authority away from the test mass,
- main interferometer feedback signals distributed in an optimized way to the suspended masses and external actuators,
- improved in-band active reduction of seismic noise,
- damping of resonances in the vibration isolation chain,
- active reduction of large-dynamic-range motions below the signal band, especially at the microseismic peak

The control issues to be considered include the nature of error signals and location of sensors, the nature and location of actuators, distribution of control authority through the hierarchy, gain/bandwidth/noise issues for the loops, ability to bootstrap into the locked state, precision of parameters (e.g., matching of actuators) and robustness of lock once achieved.

A variety of designs will be considered. Active systems near the ground have the least stringent noise requirements, and may be located outside the vacuum system and need not be vacuum compatible. Active systems nearer to the test mass certainly need to be vacuum compatible, and face tougher noise requirements, but act on lighter, dynamically simpler, loads. Another set of considerations pertains to how and where we generate the error signals to be nulled by the active system. Possibilities include external seismometers, internal sensors (with collocated actuators), the main interferometer signal, as well as signals from a dedicated auxiliary (e.g., suspension point) interferometer.

Our Controls Research effort will involve analyzing these issues, and proposing possible mechanical configurations and control topologies that meet the overall suspension design goals for both LIGO II and LIGO III. This work will primarily be carried out by Stanford and LIGO/MIT. Their work will be aided by input from the GEO group and from experience with the LIGO I system, as that information becomes available. Research on noise and dynamic range properties of sensors/ actuators will be an activity at PSU. An external pre-isolator using extra-vacuum air bearings will be investigated by LIGO/MIT.

3.6.1 Controls for LIGO III

Advanced research aimed at LIGO III will also be carried out on several other approaches which address controls issues in different ways. Since the existing system will be inadequate for the required suppression, a design starting from basic principles will be developed at Stanford. Low frequency passive pre-isolators such as an inverted pendulum (as used in the VIRGO design) will be studied by LIGO/Caltech as well as filtering elements optimized for vertical noise suppression. High-gain active systems (with low-noise seismometers) aimed at substantial signal-to-noise improvements at low frequencies will be studied at JILA. Advanced isolation and alignment control using hexapod platforms inside the vacuum chamber will be studied at Stanford University.

The use of an additional interferometer to monitor and control the suspension point motion will be pursued by CEGG. Alternatives to fiber suspensions (utilizing magnetic or electrostatic forces) are also being explored by the CEGG group.

3.7 Isolation

Here we discuss systems that reduce the seismically-driven test mass motions in the GW signal band, which begins at approximately 30 Hz for LIGO II and lower for more advanced designs. In this region the goal is to make the seismically driven motions small compared to other more fundamental noise sources, such as thermal noise. There is some overlap with controls, of course, as control systems may be used to complement passive isolation stages. Reduction of seismically driven motion at control-band frequencies (<20 Hz) is also very important, although not for the direct improvement of signal-to-noise density at those frequencies. The issues involved are discussed in the Controls Research section above.

Horizontal GW-band Isolation: In our Baseline, we assume the LIGO I stack will be part of the LIGO II isolation system. The principal new element will be the all-fused-silica pendulums. Their construction, and tests for attenuation, parasitic resonances, other defects in isolation properties (along with consequent modifications of these pendulums), is a focus of our effort. GEO will characterize their system, and a LIGO-sized variant will be constructed and studied at LIGO/MIT (the latter via the sharing of a GEO prototype with LIGO). As prototypes are developed to demonstrate component and attachment techniques (Stanford, LIGO/Caltech) they too will be characterized. A specific effort to characterize motion cross couplings due to imperfections will be undertaken at PSU. Attenuation of GW-band motion via the pre-isolators (see Controls, above) will also be investigated

Vertical GW-band Isolation: Although in principle the only test mass motions that cause noise are those along the interferometer optic axis, some cross-coupling from other degrees of freedom is inevitable. Vertical noise is guaranteed to enter at least at the level of 3×10^{-4} level due to the curvature of the Earth, but may well enter more strongly due to asymmetries of the suspension. The problem of vertical noise is more severe because a pendulum is stiffer in the vertical than the horizontal---15 to 20 Hz resonance frequency in vertical is typical, while the horizontal resonance is at 1 Hz.

Several soft stages of vertical isolation will need to be added to the LIGO II suspension so that vertical noise will not dominate the seismic noise budget. Our design effort will use trapezoidal cantilever springs (based on the VIRGO approach) as a starting point. GEO, LIGO/Caltech/MIT, and JILA will address these issues.

Characterization of first-generation systems: In addition to the design of new components for LIGO II, it is necessary to better characterize the LIGO I stacks that we assume will continue to be a part of the LIGO II vibration isolation system as well as the initial suspensions. Our models need to be improved, especially those related to quantifying and understanding cross-coupling. As our understanding of this sub-system improves, it will enable us to refine our requirements on the new parts of the system.This work will be carried out by LIGO/Caltech/MIT and PSU. This effort will also benefit from similar work on the GEO, VIRGO, and TAMA suspensions.

3.7.1 LIGO III Isolation efforts

Significantly better seismic isolation will be required for LIGO III to realize the benefit from the needed reduction in thermal noise. It is anticipated that the isolation system will be completely replaced for this phase, and this allows much more design freedom and an opportunity to make a coordinated design including both the controls and the isolation aspects of the interferometer. A synthesis of active and passive approaches is most likely to lead to the best solution, and the distinction between isolation and controls issues practically disappears.

Alternatives to the LIGO I stacks are being pursued with an eye on LIGO III, but with the possibility of partial application in LIGO II should research justify it. A multiple-pendulum system, based on the VIRGO design, is under study at LIGO/Caltech. Improvements and simplification of the vertical isolation will be studied on a several-stage prototype.

High-gain active systems address in-band noise as well as reduce RMS motions. These are discussed under Controls, above.

Characterization of the ground motion at both LA and WA leading to the fluctuating Newtonian gravitational background (‘gravity gradient noise’) will be performed by teams from Louisiana Tech and the University of Oregon, and will be (for our working group) coordinated by PSU and with Thorne’s group at Caltech. This may lead to means to reduce this noise source for the most advanced interferometer designs.

3.8 Thermal/excess noise research

Thermal noise in the suspension and test mass will limit the performance of the LIGO II interferometer (and in all probability all more advanced designs) over a substantial frequency band. The test mass thermal noise limits the ability to profit from changes in the optical configuration and from reductions in the shot noise in general. The suspension thermal noise acts as a ‘soft brick wall’, limiting the lowest frequency for which we have the greatest sensitivity. Pushing the thermal noise (and limiting excesses above thermal noise) to levels at which astrophysical signals can be detected and studied is the goal of this line of research.

Fused silica is a material with a remarkable combination of optical and mechanical properties, which makes it the best choice at present for the critical interferometer parts that are the test masses and suspensions. This point has long been stressed by the Moscow State group. A key breakthrough in our ability to exploit all-fused-silica suspensions was the development of silicate bonding at Stanford. Application of that technology to interferometer suspensions has been pushed by the GEO group.

Fused silica’s good properties, and the existence of a practical and robust assembly (and repair) procedure, are the basis of our starting assumption that the LIGO II suspension will be entirely made of fused silica. But that assumption needs to be tested and justified on a variety of counts.

- We need to measure the dissipation levels (that determine the levels of thermal noise, according to the Fluctuation-Dissipation Theorem) of the various fused silica components and assembled systems, to guarantee that we can reach the levels limited by the best material properties. This will be carried out by the standard technique of measuring resonance quality factors to obtain information at the resonant frequencies (Stanford, LIGO/Caltech, GEO), and by the newer relaxation technique developed at Syracuse for measurements at signal frequencies far from the resonances. Syracuse will perform experiments (measurements of Q) to learn about dissipation in optical coatings, in collaboration with Stanford; a planned collaboration with Iowa State will develop means to calculate the noise from localized losses and arbitrary shapes.

- We need to verify that we do indeed achieve the expected thermal noise levels, without significant amounts of excess noise; both stationary (best characterized in the frequency domain) and non-stationary (studied in the time domain) performance are issues. A good beginning to this test can be made by measuring the statistics of the thermal excitations of, for example, wire resonances, as pioneered at Moscow. They will extend their work to all-fused-silica suspensions. A similar experiment is being carried out at Stanford. When feasible, this needs to be supplemented by direct off-resonance measurement of the thermal (or excess) noise spectrum. Several groups around the world are developing special purpose interferometers for the latter test; within our collaboration we have an experiment at LIGO/Caltech concentrating on the internal test mass noise (others, in VIRGO and ACIGA), address pendulum thermal noise). The techniques we develop to understand and eliminate excesses, will also be used to ensure that more ‘technical’ noise sources (electronic, seismic, creaking, rubbing due to cabling, etc.) are held to required levels. There will be trades to be made to minimize the overall noise performance which involve both ‘excess’ and ‘fundamental’ noise sources (influencing e.g., the thickness of fiber).
- We need to qualify production techniques to ensure that assembled suspensions meet all of the specifications, including those related to thermal noise; separate measurements of the Q of components does not guarantee that the complete system will realize its potential. Production of fused silica fibers is planned by LIGO/Caltech, and assembly techniques will be refined by GEO and Stanford. Tests of prototypes at GEO, Stanford, and LIGO/MIT will ensure that the complete suspensions perform correctly.
- Alternative materials, possibly just for use at end test masses, will be pursued for possible inclusion in a LIGO II installation. Sapphire can have much lower thermal noise, and has other desirable properties, but at the moment can not be produced with all required optical properties in sizes large enough for LIGO test masses. A LIGO/ACIGA/VIRGO collaboration has been established to develop sapphire for test mass applications. Complementary measurements will be made of commercial samples already acquired by Stanford, by Q measurement and by the relaxation method. Assembly techniques will be developed at Stanford.

3.8.1 LIGO III Research

Thermal noise research will also point ahead to possible further improvements that may only come with LIGO III. If progress is sufficiently rapid, though, some of these developments might “jump the queue” (through a careful evaluation of the risk and advantages of incorporation in an early design) and become part of LIGO II. Advanced research topics include:

- Tests of alternative materials. Sapphire will continue to be developed as described above. YAG has promise of easier polishing and isotropic optical propagation; its material loss properties are, however, not well known. Silicon also has very low dissipation levels, and might be a candidate for applications not requiring transmission through optics (Stanford). For fibers/ribbons too, these materials and others might allow substantial reductions of the pendulum thermal noise (Stanford, GEO). The planned collaboration with Iowa State will develop means to calculate thermal noise due to anisotropic materials and losses. Alternatives to fiber suspensions (e.g., magnetic or electrostatic) may lead to reduced thermal noise (CEGG).

- Several applications could follow from the ability to monitor the excitation of violin modes in fibers, e.g., damping of excess excitation events. Development of appropriate sensors will be pursued by Syracuse. The Moscow work on excess noise will also of necessity involve development of sensor technology, which may very well be applicable for this function as well. Part of the GEO design is a damping system for acquisition transients.
- Reduction in the actual and/or perceived thermally-driven motion through a combination of sensing of the fiber motion and placement of the optical axis with respect to the mechanical degrees-of-freedom. MSU will continue to pursue this theoretically, with experimental tests likely to follow within the working group.
- Significant reduction in thermal noise could come from cooling the suspensions to cryogenic temperatures, both from the explicit dependence of thermal noise on the temperature and from the fact that for many materials losses are reduced as the temperature goes down. (This property is not shared by fused silica, unfortunately, so cryogenic designs must be based on other materials, such as sapphire.) Development work on overall cryogenic engineering will be led by LSU. The LSU group will also pursue suspension designs that cool pendulum fibers while keeping fused silica test masses warm. Possible all-cryogenic sapphire designs will be pursued at a low level at Syracuse and Stanford.
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3.9 System tests

The research described above will be performed on prototype suspension elements which are best suited to test the design in question; an example would be a cantilever spring and its control system, which could be tested using a simplified pendulum made with steel wires and aluminum masses. However, once a relatively complete suspension/isolation system design is available, tests which directly address its functionality in an interferometer will be needed. These tests will determine if the requirements for the subsystem are met: attenuation, distribution of control, acquisition of operation of the optical system, and ultimately the noise performance insofar as it can be measured. The tests will be performed to help guide the final design process, and some iteration is anticipated. Tests of parts of isolation and suspension systems can be carried out at the Stanford Engineering Test Facility (ETF), and the MIT Test Interferometer (MITTI). The specific configuration of suspensions and the optical system will be chosen to best illuminate the design performance.

An additional role for the tests is to allow the interfaces to the existing LIGO infrastructure to be worked out, and to ensure that the installation of the new system can be performed in a way which limits the impact on the ‘downtime’ of LIGO. The MIT Test Interferometer (MITTI) will play a central role in these tests.

The specific tests planned are

- controls tests of prototype suspensions (ETF). This will involve setting up two separated suspensions as an optical cavity and testing models for acquisition and operation.
- controls/isolation tests of advanced ‘hexapod’ high-gain sensor/actuators (ETF).
- transfer function tests of prototype suspensions (MITTI). A full-scale suspension will be installed in a LIGO vacuum equipment chamber, on a LIGO I stack, and the net isolation and control characteristics of the assembly measured and iterated as needed.
- noise performance tests of prototype suspensions (MITTI). A high-sensitivity test, using interferometry, will be made of a system using several of the new suspension/isolation/pre-isolation planned for LIGO II.
- interface checks and installation procedures (MITTI). Engineering units of the LIGO II mechanical system will be installed in the MITTI to ensure minimum downtime for the upgrade of the LIGO site interferometers.

Before either the ETF or the MITTI are ready to perform research, the infrastructure must be established and the installations readied to receive test suspensions. In addition to the vacuum systems, there is the need to develop the measurement systems and readout means for specific tests. For both installations, significant participation by the entire working group is expected; both facilities are open to the LSC research effort.

Table 5: Tasks, Coordinators, Active Groups

Internal Requirements (Gonzalez)	PSU, LIGO/MIT, Stanford
Configuration (Hough)	Joint activity, Design Summit
Controls (How)	Stanford, GEO, LIGO/MIT, PSU, JILA, CEGG
Passive Isolation (Giaime)	LIGO/Caltech, LIGO/MIT, PSU, JILA, GEO
Thermal/Excess Noise (Saulson)	Syracuse, LIGO/Caltech, Stanford, MSU, GEO, CEGG
Systems (Shoemaker)	LIGO/Caltech, LIGO/MIT, Stanford, PSU

4 LASERS AND OPTICS

4.1 Introduction

In this section of the white paper we discuss laser and optics research and development for LIGO II and LIGO III. Fundamentally we are concerned with the standard quantum limit, however, several technical problems must be overcome before reaching this fundamental limit to interferometer sensitivity. These problems include: laser power fluctuations, laser frequency and modal noise; core optics absorption and scatter losses; photodiode quantum efficiency and power handling; and the power handling and optical efficiencies of various conditioning optics, modulators and optical cavities.

The lasers and optics research plan involves both evolutionary improvements to existing technology and materials for LIGO II and revolutionary changes for LIGO III. Evolutionary improvements to core optics performance and laser power are within the range of current technology and in several cases already reach the performance needed for LIGO II. On the other hand reaching the sensitivity level of LIGO III may require novel and as yet untested ideas such as advanced interferometer configurations, shorter laser wavelength and the development of new core optics materials.

4.2 Core Optics

If we use fused silica for the LIGO II core optics the development path from LIGO I to LIGO II involves only an evolutionary development effort to allow a factor of 30 higher stored power in the interferometer arm cavities made up of an increase of a factor of 10 in input laser power and a factor of 3 increase in the power recycling factor.

The LIGO II goal for micro-roughness and substrate absorption has already been demonstrated. Meeting the surface figure goal will require a factor of 3 improvement in metrology and fabrication. Thus achieving the specifications of LIGO II will require continued interaction and development with coating and polishing vendors but is probably within the range of current technology. Reducing coating absorption by a factor of 10 will be much more difficult to achieve because at this time we have no idea of its cause. Nevertheless improved coating loss combined with active core optics compensation as discussed below should allow an increase of 30 in circulating power.

An important area of core optics research is the selection of materials that offer a reduction of internal thermal noise and improved thermal conductivity. Promising candidates are Sapphire, YAG and spinel all transparent materials with high thermal conductivity. Sapphire is known to have a lower mechanical loss factor than fused silica. YAG and Spinel are hard cubic crystalline oxides. It must be demonstrated that they can be grown in large sizes and polished to LIGO's exacting specifications. The use of one of these crystalline materials would constitute a revolutionary change and entails risk for LIGO II. Nevertheless, to reach LIGO III sensitivity a change in core optics material is certainly necessary and beginning the development work now on likely candidate materials would be prudent.

Recommendations for LIGO II

1. Continue the development of low loss silica and sapphire and measuring their absorption loss and uniformity at 1064 nm. Begin a similar program on YAG and spinel.
2. Begin systematic measurements of the absorption loss of coatings and determine the absorbing species to provide feedback to coating vendors.

Recommendations for LIGO III

1. In collaboration with the other two working groups prepare a list of candidate materials and rank them according to the likelihood that they can be figured, polished, coated and fabricated into a suspension system.
2. Select the best 2 or 3 materials from the above list and have them polished, figured and measured.
3. Measure substrate absorption in candidate materials at 1064 and 532 nm.
4. Measure coating absorption at 1064 and 532 nm.

4.3 Core Optics Contamination

The LIGO vacuum system will contain a number of porous materials that are potential sources of gas phase hydrocarbons. The adsorption of a thin hydrocarbons film onto a core or mode cleaner mirror can increase surface roughness and optical absorption. The contaminant layer will add to the surface absorption and thus contribute to the non-uniform heating which will distort the surface figure and induce a thermal lens or distort the mirror figure. Thus the presence of a contaminant film can cause a significant degradation in interferometer sensitivity.

Because of the complexity of the surface chemistry and possible photo-chemical interactions the absorption of these contaminating layers at a particular wavelength and optical intensity can only be determined empirically. LIGO has a research effort underway in which small Fabry-Perot test mirrors are exposed to suspected contaminating materials. The Fabry-Perot is operated at 1064 nm with the maximum optical intensity expected in LIGO I. The cavity storage time determines the total loss while a measure of the cavity transverse mode spacing gives the absorption loss. In this way it is possible to disqualify materials which cause unacceptable optical losses.

In LIGO III the problem of contamination will become even more severe as lower loss optics and higher circulating power and possibly shorter wavelengths are used. The use of shorter wavelengths will almost certainly increase the risk of contamination problems because the likelihood of surface photo-chemistry increases sharply with shorter wavelength. Moreover, the problem of optics contamination will become extreme if it becomes necessary to use cryogenic mirrors that will have a much higher molecular sticking coefficient than room temperature mirrors. This problem will require an ongoing effort to insure that optics contamination remains acceptable.

LIGO II Recommendations:

1. More information needs to be gathered on contaminants, their surface chemistry and absorption at 1064 nm.
2. Current practice in the semiconductor and optics fields for in situ surface cleaning should be investigated and if experience shows a need for in situ mirror cleaning small scale experiments should be undertaken to determine the viability of different approaches

LIGO III Recommendations:

1. More information needs to be gathered on contaminants and their absorption at 532 nm.

2. Measurements need to be made on cryogenic adsorption of contaminates.

4.4 Active Compensation of Core Optics

LIGO I was designed for a laser input power of only 6 watts, nevertheless, bulk absorption in the input mirrors and beamsplitter substrates are predicted to induce thermal lensing which must be compensated by incorporating an additional curvature into the recycling mirror. In LIGO II, which will have at least 10 times higher circulating power at the beamsplitter, this problem will be worse. It is likely that the circulating power of LIGO III will be limited by thermal distortion of its optics. One approach to solving this problem is to improve the core optics materials. However, materials problems have no guaranteed solution and when the possibility of an engineering fix to a materials problem arises it should be pursued. Active feedback control of core optics to compensate for the thermal distortions induced by laser beam heating presents just such a possible engineering fix.

By depositing heat in a confined zone by either a fixed configuration of heaters or by scanning across the face of the optic, it is possible to introduce a thermal component which cancels virtually any form of distortion (indeed, even initial figure distortions unrelated to laser beam loading may be compensated). Initial tests by Mueller at Hannover scanned a Nd:YAG laser over a mirror to correct for thermal lensing in a visible-light interferometer and significantly improved the fringe contrast. By using either a 10.6 micron CO_2 laser, which is strongly absorbed in fused silica, or a long-wavelength solid state laser which has a longer optical absorption depth in the test mass material the compensation could be done with a low power beam. Feedback control also requires a sensor for the parameter to be compensated. Both Shack-Hartmann wavefront sensors and a spatial extension of the wave-front gradient sensing technology developed for LIGO I look promising.

LIGO II Recommendations

1. Develop sensors and actuators for active core optics control.
2. Build a small table-top apparatus to test sensing and actuation schemes.

4.5 Diffractive Optics

LIGO II will require a circulating power in excess of a kilowatt and LIGO III will require even higher power, the use of a new higher Q material for the core optics and possibly shorter laser wavelengths. Moreover, the use of high mass core optics to reduce the effects of radiation pressure will mean that the level of circulating power is likely to be set by the thermal loading of the core optics and beamsplitter. Currently proposed interferometers use optical coatings on thick transmissive substrates whose surface figure will be distorted by substrate beam heating. By using all reflective optical components light propagation through the substrate is eliminated. A properly designed grating can act as a purely reflective 50/50 beamsplitter, or can be configured as a reflective input coupler in an all reflective optical cavity. In addition to eliminating substrate absorption, this approach also opens up the list of candidate materials which can be used for the core optics and beamsplitter to include opaque materials. These materials can then be selected for their high thermal conductivity, low thermal expansion coefficients and low acoustic loss at cryogenic temperatures. The decoupling of mechanical properties from bulk optical properties in the selection of materials for LIGO III is thus an important advantage.

LIGO III Recommendations:

1. The research in this area should concentrate on the development and testing of small low loss diffractive optical components.

4.6 Modulators, Isolators and Mode Cleaners

The optics that condition the light from the laser and deliver it to core optics components of the interferometer and the optics that deliver the light from the interferometer to the control systems are critical components of any advanced gravitational wave detector. These optics include: Electro-optic Modulators (EOM) which phase modulate the carrier to produce sidebands for length and alignment sensing and control; Acousto-optic Modulators (AOM) to intensity stabilize the carrier; Mode Cleaners provide additional stabilization of the light frequency and spatial modes of the laser beam; Faraday Isolators (FI) prevent the laser light reflected from the interferometer from corrupting the length and alignment control systems; Beam Expanding Telescopes allow for the efficient mode-matching of the laser beam into the interferometer core optics.

In order to meet the LIGO II and III sensitivity goals, the conditioning optics will be required to handle laser powers approaching 100 W (10 times of those used in LIGO I). In addition, these power levels must be maintained over long periods of time. In this section, we consider the impact of the increased power on modulators, isolators and mode cleaners, and outline the research necessary to address these effects and possible solutions.

Modulators and Isolators

There are four ways that modulators can limit the sensitivity of interferometric gravitational wave interferometers: First, in a pre-interferometer modulation scheme that requires that the full laser power to be transmitted beam absorption induced heating can distort the wave fronts. Second, photorefraction can result in intensity dependent refractive index variations that destroy the spatial coherence of the light beam. Third, irreversible physical damage can occur in the modulator material or coatings. Fourth, frequency (phase) modulation (FM) to amplitude modulation (AM) conversion can produce spurious RF signals at the main photodiode output.

LIGO II Recommendations

1. Perform thermal lens testing and wavefront quality testing on large aperture $LiNbO_3$ at 100 w and if significant distortion occurs develop thermal compensation methods.
2. Perform long term tests at high power to verify crystal stability.
3. Investigate FM - AM conversion at LIGO II power levels.
4. Measure thermal lensing and wavefront distortion measurements in AOMs at 100 w.

Optical Isolators

The materials used to make optical isolators have even more severe power handling problems than either amplitude or phase modulators therefore we recommend a similar program of research for these devices. In addition, the requirement of putting one isolator inside the vacuum system places additional requirements because of the danger of contamination of the core optics.

LIGO II Recommendations

1. Measure the wavefront distortion induced by Faraday isolators at 100 watts.
2. Measure the depolarization effect in Faraday isolators at 100 watts.
3. Demonstrate outgassing rates consistent with LIGO II vacuum requirements.

Mode Cleaners

The suspended input mode cleaner serves several functions. It spatially filters the laser mode, reduces amplitude and frequency noise of the light, is used in the frequency stabilization loop, decreases beam wiggle, and improves the polarization quality. The LIGO I mode cleaner has a finesse of 1550, so there is considerable stored power. Consequently, the mode cleaner optics suffer from similar power handling and contamination requirements as the core optics of the interferometer. The present design for LIGO does not contain an output mode cleaner, although such a device may reduce incident power on the photodetector by rejecting scattered and mode-mismatched light from the interferometer. With the higher power levels required in the LIGO II interferometer, an output mode cleaner may be required.

LIGO II Recommendations

1. Investigate power handling in mode cleaners.
2. Perform a design study for an output mode cleaner.

4.7 Photo Detector Development

LIGO I uses twelve commercially available InGaAs PIN photodiodes in parallel to provide adequate signal-to-noise ratio when illuminated with 1.2 W of cw dark fringe power and uses a fast electro-optic shutter to provide protection against the multi-Joule transients which results whenever the interferometer unlocks. To take advantage of the substantial sensitivity improvements afforded by higher power lasers, photodiodes with a factor of 10 improvements for most specifications are required.

CW and transient power handling can be expected to improve with increasing device area; however, junction capacitance and residual resistance also increase sharply with area. As a result the RF impedance of the larger devices (larger than about 3 mm, among current commercial offerings) is too low to afford adequate SNR. These and other tradeoffs haven't been optimized with LIGO in mind. The constraints of high power, high SNR RF operation, high quantum efficiency and other optical and electronic properties found in LIGO do not apply for other applications and so manufacturers have not been driven in these directions by other markets. As an example, junction-case thermal impedance of approximately 20 C/W is common for LIGO I InGaAs PIN diodes, an order of magnitude higher than is typical of “high-power” electronic devices such as power transistors. Moreover, novel structures, such as the back-illuminated stack promise significantly higher quantum efficiency with even better electrical properties. At the moment, we cannot predict where intrinsic materials limits to InGaAs diode performance will ultimately lie. However, we can be confident they are well beyond the capabilities of current off-the-shelf devices.

LIGO II Recommendations:

1. Experimental InGaAs device research to develop higher power photo detectors.
2. Laboratory optical and electronic testing of prototype devices.
3. Transfer of device designs to industrial partner for packaging and production.
4. Photodiode testing in the LIGO I interferometer.

4.8 Advanced Lasers

The path from LIGO I through LIGO II to LIGO III will require increasing laser power and possibly shorter wavelength. This will involve the development of diode laser pumped slab optical gain stages that can be used either in unstable resonator injection locked power oscillators or as a multipass power amplifier. Technical issues that effect the selection of a particular laser design include amplitude and frequency noise, spatial mode control, output power and the availability of good frequency and power actuation for feedback control. Other systems issues include operational reliability, maintainability, minimizing the number of single point failure modes, and commercial support for continuing technology development.

Output Power and Nonlinear Frequency Conversion

The two most common approaches to providing high power laser radiation are the use of unstable optical resonators and the use of a master oscillator followed by a power amplifier. While LIGO I has selected the latter design either of these approaches is likely to work for LIGO II using Nd:YAG as the gain medium and the current LIGO I laser as the master oscillator. Converting the 1064 nm to 532 nm is at this time limited by the availability of reliable high power nonlinear optical materials.

LIGO II Recommendations:

1. Compare a prototype injection-locked unstable resonator and a MOPA system.
2. Develop a 100 W class diode laser pumped Nd:YAG laser.

LIGO III Recommendations:

1. Frequency convert the 100 W laser to 532 nm and characterize the noise.

2. Operate the frequency doubler long term to test for materials degradation and damage.

Amplitude and Frequency Noise

The amplitude noise at low frequency in injection locked oscillators and amplifiers is largely determined by the gain fluctuations resulting from the diode laser power fluctuations. At higher frequencies, however, there are differences in performance between injection locked lasers and amplifiers. Injection locked oscillators have optical cavities which produce spatial and temporal filtering while amplifiers have no such filtering. Nevertheless, high gain solid state lasers have low output coupling and consequently there is little temporal filtering at the LIGO modulation frequency and so practically speaking both injection locked lasers and amplifiers require a fixed spaced Fabry-Perot cavity for temporal filtering as is done in LIGO I. A thorough theoretical understanding and experimental determination of the excess quantum noise of an unsaturated MOPA system now exists and the MOPA approach has been selected by LIGO I. However, to achieve high efficiency the MOPA must be operated in a highly saturated regime, the regime in which an injection locked oscillator naturally operate because of this optical feedback and consequent gain saturation, and the noise of such free space saturated systems remains unexplored.

Frequency noise in diode laser pumped solid state lasers results from the pump diode laser power fluctuations which produce a time varying optical path length in the gain medium. All of the low power single frequency diode laser pumped solid state lasers which are used as master oscillators are pumped by a small number of low power, low amplitude noise, diode lasers and have approximately the same free running frequency noise characteristics. Higher power injection-locked oscillators and MOPAs which use several high power diode lasers usually have a frequency noise spectrum dominated by the master oscillator.

Spatial Modes

The spatial modes of all high power solid state lasers are poor with much of their power in higher order transverse modes. As a consequence, spatial mode compensation may be required which can be performed with a either a Fabry-Perot cavity or adaptive optics or both. The injection locked laser is likely to require less additional spatial mode control because of the spatial mode selectivity of the optical cavity.

Table 6: Tasks, Active Groups

Core Optics (Whitcomb)	LIGO/Caltech, Stanford, Syracuse, GEO
Contamination (Camp)	LIGO/Caltech, Stanford
Active compensation (Zucker)	LIGO/MIT, Stanford
Diffractive Optics (Munch)	CEGG, Stanford, ACIGA/Adelaide
Ancillary Optics (Reitze)	UFlorida, Stanford, LIGO/MIT
100 W Laser (Byer)	Stanford, LIGO/Caltech, ACIGA/Adelaide, GEO

5 APPENDIX: APPROXIMATE MANPOWER AND COSTS

The estimates for manpower are based on the plans described in this document for the research and development phase of the effort. They include the research targeted at both LIGO II and LIGO III, but they do not include the final design engineering, fabrication, installation, or commissioning manpower costs. They are based on the individual working group estimates and are subject to change if new technical difficulties arise. The figure includes all scientific staff, whether supported by the NSF or otherwise (faculty, non-US collaborators). While there are some variations year-by-year in our estimates (in particular some growth with time), a constant value is a good approximation.

The equipment estimates are based on crude extrapolations from the LIGO I costs and are only for LIGO II capital equipment costs; they also do not include the manpower to install or commission the equipment.

The downtime is also based very roughly on LIGO I installation and initial shakedown times and may be shortened with more experience working with the LIGO site equipment. The installations can be implemented in a staged fashion, with the double suspensions being first, the 100 W laser next, the Signal-tuned interferometer as third, and alternate test masses when ready.

Table 7: Manpower, Costs, and Availability impact

Working Group	R&D Manpower (FTEs, per year)	Near-term focus	Capital equipment, for 1 interferometer, installed at LIGO sites	Downtime (installation and initial shakedown)
Suspensions and Isolation	43	Double suspensions	2.3M	12 months
Lasers and Optics	20	100 W Laser sapphire test masses	0.7M 0.8M	4 months 4 months
Configurations	9	Signal-tuned interferometer	0.8M	3 months