LSC White Paper on Detector Research and Development

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11 September 1999 - LIGO T990080-00-D

Summary and Introduction

This document presents a recommended program of research and development to support improvements to the Laser Interferometer Gravitational-wave Observatory (LIGO). The program is the result of research undertaken by the technical development groups of the LIGO Scientific Collaboration (LSC), and subsequent discussion by the LSC at large. A companion document presenting the LSC recommended program in detector characterization and data analysis is also available.

The recommended program is tightly focused around a reference design for LIGO II, which is planned to be a quantum-limited interferometer with a very significant increase in sensitivity over LIGO I. A smaller but vital continuing research plan for future detector development is also laid out. The progress in the baseline plan and the research will be the subject of a yearly report by the LSC. The report will also present iterations and adjustments to the plan as determined by new information gained from the research. A conceptual plan for the schedule and projected cost for the full-scale implementation of the baseline has been developed by the LIGO Laboratory in close coordination with the LSC research plan, and is a companion document to this one[1].

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 100 Hz,
- the assessment of the technical maturity and feasibility of the improvement,
- the increase in detection range of anticipated 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 that:

- LIGO I detections, if any, do not lead to significant revisions in the goals or sensitivity targets,
- the first changes will be made after a significant observing period with the initial LIGO detector,
- changes in the initial LIGO detector will be introduced in such a manner that observation (by LIGO and by the gravitational wave detection network) will be minimally impacted.

The LIGO II upgrade is planned for incorporation in the LIGO at the beginning of 2005. The significant improvements in the LIGO sensitivity are based on the engineering development of

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[1] LIGO II Conceptual Project Book, LIGO M990288-00-M

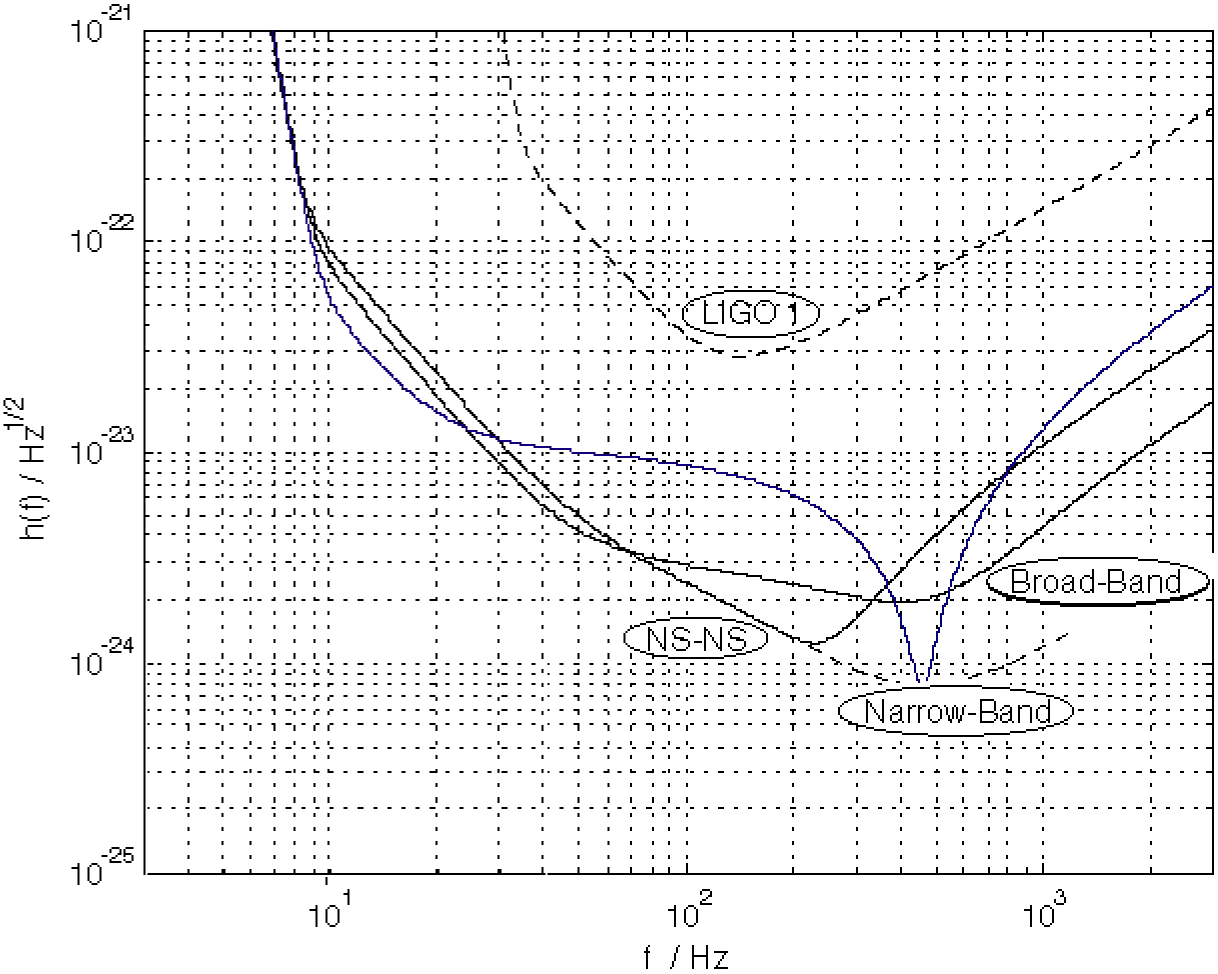

Figure 1. Sensitivity of proposed LIGO II interferometer. The curves represent unity signal to noise for a single 4km interferometer. The sensitivity for the two observatories, averaged over all angles and both polarizations, for a S/N of 5, lies a factor of 11 above these curves.

existing technology for some subsystems and more ambitious development programs for others. On a much longer horizon, the elements of the LIGO III program comprise a basic research effort 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 top-level performance for the LIGO II program is illustrated in Figure 1, which shows the strain sensitivity (in spectral density) for unity signal-to-noise and a single detector. The uppermost is the performance of the initial LIGO interferometer. For LIGO II, signal recycling shapes the shot-noise limited response of the interferometer, allowing optimization for a given source, e.g., a NS-NS binary inspiral ('NS-NS') or selection of a narrow frequency band to focus on a particular gravitational-wave signal (e.g., 'Narrow-Band', with the dotted line indicating the locus of narrow-band sensitivity curves), or a wide-bandwidth mode ("Broad-Band").

Physics Reach

Excellent surveys of potential sources and their observability with interferometric detectors can be found in the literature[2]; here we list the sources detectable by LIGO-I and LIGO-II, using both Hanford and Livingston observatories, assuming the anticipated data analysis techniques. Neutron stars are denoted NS; black holes, BH. Unless otherwise indicated, the NS's in our examples all have masses of 1.4 M_o (solar masses) and the BH's, 10 M_o. For each source, the interferometer response is assumed to be coarsely optimized using the flexibility of the RSE configuration (as shown in the curves in Figure 1). We assume a detection threshold set for a false alarm rate of one percent in a search lasting one year with the full LIGO network (two 4 km and one 2 km interferometers).

Inspiral of NS/NS binaries: Detectable to distance 20 Mpc by LIGO I; 450 Mpc (a cosmological redshift of $z = 0.1$) by LIGO II.

Inspiral of NS/BH binaries: Detectable to 40 Mpc by LIGO I; 1000 Mpc ($z = 0.2$) by LIGO II.

Inspiral of BH/BH binaries: Detectable to 100 Mpc by LIGO I; 2000 Mpc ($z \sim 0.5$) by LIGO II.

Tidal disruption of the NS in a NS/BH Binary: The tidal disruption begins at a frequency that depends strongly on the (unknown) neutron-star radius and thence on its unknown equation of state. LIGO I could distinguish a 15 km NS from a 10 km one out to about 10 Mpc; LIGO II could do so out to 400 Mpc.

BH/BH mergers: The merger signals will teach us much about the highly nonlinear, large-amplitude dynamics of space-time curvature. Based on rough estimates of the signal characteristics (which need firming up in supercomputer simulations) and assuming optimal signal processing, the amplitude signal-to-noise ratios for mergers at 1000 Mpc distance ($z = 0.24$) are as follows:

- 10 M_o/10 M_o -- $S/N = 0.5$ for LIGO I, 10 for standard LIGO II;
- 25 M_o/25 M_o -- $S/N = 2$ for LIGO I, 30 for standard LIGO II;
- 100 M_o/100 M_o --- $S/N = 4$ for LIGO-I, 90 for standard LIGO II.

R-mode oscillations of a newborn neutron star: Current models suggest that these oscillations will be driven unstable by gravitational radiation reaction; the wave emission would then spin the star down from its initial spin (which must be larger than ~100 revolutions per second for the instability to act), to ~100 rev/sec in a time of about one year. LIGO I can detect these waves to a distance of 1 Mpc; LIGO II, to 20 Mpc (reaching the Virgo Cluster where there are several supernovæ per year).

The spinning NS's in Low-Mass X-Ray Binaries (LMXB's): Assuming that the NS is being buffered into its observed spin rate by a balance between accretion spin-up torque and gravitational-radiation-reaction spin-down torque, the strengths of the gravitational waves can be inferred directly from the observed accretion-induced X-ray flux. For the strongest such source, Sco X-1 (waves at ~500 Hz), the ratio of the predicted signal strength S to that required for 99% confident detection ($S_{99\%}$) is

- $S/S_{99\%} = 0.1$ (undetectable) for LIGO I;

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[2] E.g., K.S. Thorne, "Probing Black Holes and Relativistic Stars with Gravitational Waves," in *Black Holes and Relativistic Stars*, Proceedings of a Conference in Memory of S. Chandrasekhar, ed. R. M. Wald (University of Chicago Press, Chicago, 1998), pp. 41—78; gr-qc/9706079.

- $S/S_{99\%}$ = 2 for standard LIGO II;
- $S/S_{99\%}$ = 4 (i.e., detectable with extremely high confidence) for wide-band LIGO II;
- $S/S_{99\%}$ = 10 for narrow-band LIGO II in a 3month search centered on Sco X-1's frequency - which means that such a targeted search can detect an LMXB with X-ray flux 100 times lower than Sco X-1.

Spinning NS's in the Galactic core with f~200 Hz: There is a maximum ellipticity that a NS crust can support; it is estimated to lie somewhere in the range $\varepsilon \sim 10^{-4} - 10^{-6}$. Spinning NS's in the Galactic core, with $f \sim 200$ Hz, can be detected by LIGO-I if $\varepsilon > 5\times10^{-5}$; by standard LIGO-II if $\varepsilon > 2\times10^{-6}$.

Spinning NS's with *f*~1000 Hz: Neutron stars with $f \sim 1000$ Hz (spin periods ~ 2 msec) can be detected in an all-sky, wide-band search at the distance of the Galactic center, if $\varepsilon > 10^{-4}$ for LIGO I, and $\varepsilon > 4\times10^{-6}$ for narrow-band LIGO II stepping through frequencies in $\Delta f = 50$ Hz, one-week-long steps. For a one-week search in any chosen, specific direction and in any $\Delta f = 50$ Hz band near 1000 Hz, narrow-band LIGO II can reach $\varepsilon = 10^{-6}$. If the neutron star is 1000 years old or older (and thus not highly restless), LIGO II can do about 3 times better than this: $\varepsilon = 10^{-6}$ for an all-sky search, and $\varepsilon = 3\times10^{-7}$ for a targeted search.

Stochastic background: The strength of the waves in an isotropic stochastic background is described by $\Omega_{gw} \equiv$ (energy in a bandwidth equal to frequency)/(energy to close the universe if there is no cosmological constant). LIGO I measures this Ω_{gw} most accurately in a band centered on about 70 Hz where the overlap function between the two LIGO Observatories is small, with LIGO II profiting from the increased overlap below 70 Hz. The limits on detectability for a 'flat' spectrum are $\Omega_{gw} = 10^{-5}$ for LIGO I, and $\Omega_{gw} = 3\times10^{-9}$ for LIGO II.

In summary, the planned changes to LIGO would make significant improvements in our ability to observe specific anticipated gravitational wave sources as well as offering an increase in both bandwidth and sensitivity which will aid in 'blind' searches. At the sensitivities of LIGO I it is plausible, but not probable, that gravitational waves will be detected. By contrast, LIGO II reaches a sensitivity level where the best current estimates suggest that a number of sources should be detectable, with a signal-to-noise for near sources which could allow detailed quantitative comparisons with astrophysical models.

Summary of Reference Design

We give here a brief description of the changes involved in the LIGO II upgrade. A more complete description of the Reference Design can be found in the Appendix to this document.

The basic optical configuration is a power-recycled and signal-recycled Michelson interferometer with Fabry-Perot “transducers” in the arms. Using the LIGO I design as a point of departure, this requires the addition of a signal recycling mirror at the output “dark” port, and changes in the RF modulation and control systems. This additional mirror allows the gravitational-wave induced sidebands to be stored or extracted (depending upon the state of “resonance” of the signal recycling cavity), and leads to a tailoring of the interferometer response according to the character of a source (or specific frequency in the case of a fixed-frequency source). The control system relies on a hierarchy of actuators in the seismic and suspension systems to minimize required control authority on the test masses.

The laser power is increased from 10 W to 180 W, chosen to be optimal for the desired interferometer response, given the quantum limit and limits due to available optical materials. The Nd:YAG pre-stabilized laser design resembles that of LIGO I, but with the addition of several stages of amplification following the present 10 W laser. The conditioning of the laser light also follows LIGO I closely, with a ring-cavity mode cleaner and reflective mode-matching telescope, although changes to the modulators and isolators must be made to accommodate the increase in power.

Instead of the 25 cm, 11 kg, fused-silica testmass optics used in LIGO I, the test mass optics for LIGO II are made of c-axis sapphire, nominally 28 cm diameter, 30 kg mass. Sapphire is chosen because of its higher mechanical Q, speed of sound, and density, all of which contribute to a significant reduction in the internal thermal noise. The larger mass is needed to keep the radiation reaction noise to a level comparable to the suspension thermal noise. The beamsplitter and other suspended optics are made of fused silica. Polishing and coating are not required to be significantly better than the best results seen for LIGO, and the storage time of the light in the interferometer arms remains at 1 msec but with a power recycling factor of 80 (LIGO I will have a recycling factor of roughly 50). Compensation of the thermal lensing in the testmass optics (due to absorption in the substrate and coatings) is added to handle the much-increased power.

The test mass is suspended by fused silica ribbons attached with hydroxy-catalysis bonds, in contrast to the steel wire sling suspensions used in LIGO I. Fused silica has much lower loss (higher Q) than steel, and the ribbon geometry allows more of the energy of the pendulum to be stored in the earth’s gravitational field while maintaining the required strength. The resulting suspension thermal noise is anticipated to be less than the radiation pressure noise and comparable to the Newtonian Background (“gravity gradient”) at 10 Hz. The complete suspension has three pendulum stages, and resembles closely the GEO-600 suspension. The test mass magnetic actuators used in LIGO I are eliminated (to reduce thermal noise from the permanent magnet attachments) in favor of electrostatic forces for locking the interferometer and photon pressure for the operational mode. Local sensors (electrostatic and occultation) and magnets/coils are used on the top suspension stage for damping, orientation, and control.

The isolation system is built on the LIGO I piers and support tubes but otherwise is a complete replacement, required to bring the seismic cutoff frequency from 40 Hz (LIGO I) to 10 Hz (LIGO II). RMS motions (frequencies less than 10 Hz) are reduced by a combination of active and passive techniques, principally in-vacuum. The objective is to make the seismic noise negligible at all frequencies where the interferometer response is within several orders of magnitude of the best sensitivity as limited by more “fundamental” noise sources (quantum, thermal noise).

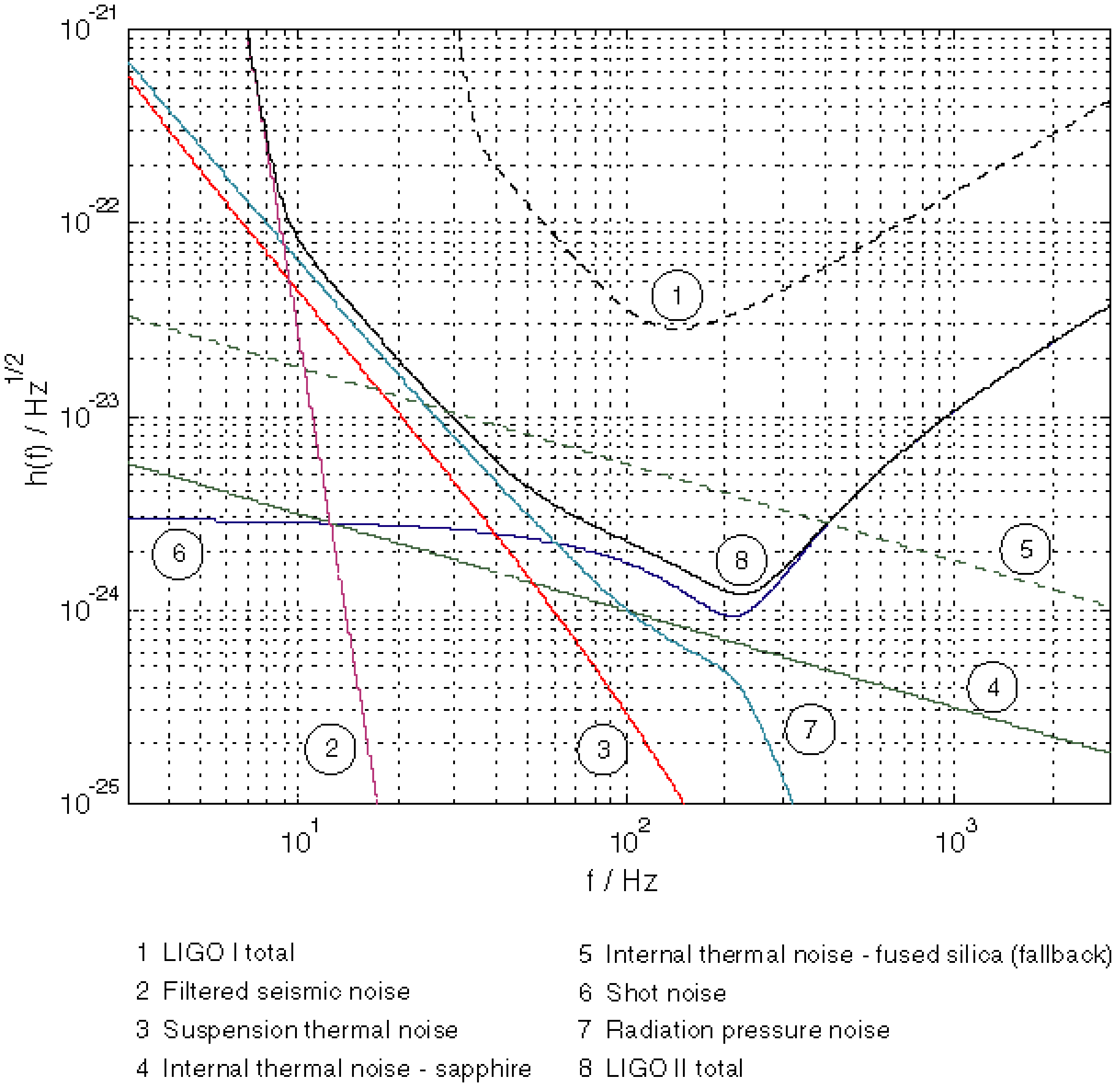

Figure 2. Noise anatomy of LIGO II.

The improvements can be identified with contributors to the overall sensitivity, illustrated in Figure 2, and the accompanying Table. The LIGO I sensitivity is shown in curve 1. Improvements in the seismic isolation allow observation down to roughly 10 Hz (curve 2). Significant reductions to the low-frequency thermal noise (curve 3) are made by employing fused silica ribbons in the test mass suspension, reducing the losses due to the attachments to the test mass and moving actuation away from the test mass. The test masses are changed from fused silica to sapphire, which with its higher density and lower mechanical loss leads to a significant reduction in the internal thermal noise (curve 4). Curve 5 shows the thermal noise expected from fused silica, and illustrates both the advantage of sapphire and a fall-back option should sapphire not be possible.

The actual overall performance is dominated by the quantum noise of sensing the position of the test masses, also shown in Figure 2. The laser power is chosen to optimize the balance (for a given desired interferometer response) between the shot-noise position sensing (curve 6) and test mass motion due to the random radiation pressure (curve 7), leading to quantum-limited performance for the 30-kg mass. The signal recycling links the radiation pressure and the shot noise; Heisenberg's uncertainty principle enforces their complementarity. The raw laser power is increased to ~180 watts, with consequent changes to the input optics. To reduce resulting thermal lensing, an active compensation system is incorporated. Finally, curve 8 is the total noise budget for this particular interferometer response (NS-NS optimized).

Table 1 gives a set of representative parameters for the LIGO II Reference Design and the corresponding value for LIGO I. Figures 1, 2, and Table 1 do not give projections for the performance of LIGO III detectors which, depending on the frequency, may provide sensitivity improvements by another decade.

Table 1. Principal Parameters of the LIGO II Reference Design With LIGO I Parameters Provided for Comparison.

Subsystem and Parameters	LIGO II Reference Design	LIGO I Implementation
Strain Sensitivity (rms, 100 Hz band)	2×10^{-23}	10^{-21}
Displacement Sensitivity (rms, 100 Hz band)	8×10^{-20} m	4×10^{-18} m
Fabry-Perot Arm Length	4000 m	4000 m
Beam Tube Vacuum Level (Chambers)	$< 10^{-6}$ torr, ($<10^{-7}$)	$< 10^{-6}$ torr
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	180 W	10 W
Optical Power at Interferometer Input	125 W	5 W
Power Recycling Factor	80 x	30 x
Input Mirror Transmission	3%	3%
End Mirror Transmission	15 ppm	15 ppm
Arm Cavity Power Loss on Reflection	1%	3 %
Light Storage Time in Arms	0.84 ms	0.84 ms
Test Masses	sapphire, 30 kg	fused silica, 11 kg
Mirror Diameter	28 cm	25 cm
Test Mass Pendulum Period	1 sec	1 sec
Seismic Isolation System	Active/Passive, 6 stage	Passive, 4 stage
Seismic Isolation System Horizontal Attenuation	10^{-8} (10 Hz)	10^{-5} (100 Hz)
Maximum Background Pulse Rate	1 per 10 years, triple interferometer coincidence	1 per 10 years, triple interferometer coincidence

The Reference Design for LIGO II we present here offers considerably better performance than the concept discussed in the 1998 LSC White Paper. This is due to new developments in suspension thermal noise, advances in prototype efforts in configurations and controls, and a change in the proposed scheduling and lifetime of the LIGO II detector. However, with this increase in performance comes an increase in the scope of required research and development. Specifically, the effort to develop sapphire test masses for both its optical and mechanical properties, and the development of a system testbed capable of assuring a realistic test of the complete mechanical design of LIGO II, will require greater research funding than a projection of current levels would indicate. These developments must take place before a Major Research Equipment grant to the LIGO Laboratory could be put in place if we are to maintain the schedule which the LSC and the LIGO Laboratory feel is optimal. One purpose of this document is to communicate the compelling scientific reasoning for this research and consequent funding increment.

The sections that follow describe the research plans in the LIGO Scientific Collaboration which are required to support the implementation schedule the LIGO Laboratory is studying for LIGO II. The much smaller research program targeted for later changes (‘LIGO III’) is also described. The Reference Design is given in the Appendix.

LSC RESEARCH PLAN

Configurations and Controls Research Plan

The objective for the configuration and associated control systems is to deliver shot-noise and radiation-pressure limited phase sensing which best exploit the optical system, thermal noise, and test mass available. 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.

Due to the complexity of the change to signal recycling (dual recycling (DR) or resonant sideband extraction (RSE)), it is 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.

Initial work is needed to find the signal recycling configuration that gives an appropriate frequency response and sensitivity for LIGO. This will be coordinated by the advanced configurations group. An early decision is needed to allow the remaining work to be more concrete.

Bench-top tests and computer modeling will continue to be used to identify candidate read-out/ control systems for DR/RSE. In addition, the tolerance of thermal effects will be an important criterion in the selection of the read-out system for further tests. Currently, groups at LIGO/Caltech, University of Florida, ACIGA/ANU and GEO are undertaking this research. The orthogonality of control signals for all degrees of freedom (signal matrix) and the signal to noise ratio (purity) of these detector outputs is being 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.

Correct operation of DR/RSE will be demonstrated on a suspended-mass prototype interferometer. Objectives for this demonstration will be to obtain reliable, low-noise performance, to study acquisition of lock for the interferometer control systems, and to characterize the tolerance of the system to optical distortions. Work on this “component prototype” will be completed by late 2002. At this stage the technical development program will be transferred to the 40m system at Caltech. Here an “engineering prototype” will be constructed to allow full integration of signal recycling techniques with LIGO control systems and suspension technology. Our program allows 2 years for this stage. Signal recycling would then be ready for implementation on a LIGO interferometer.

The first prototype stage will be coordinated by the AIC. The engineering prototype will be organized and operated by the LIGO Laboratory. University of Florida will be closely involved in both prototype stages and will facilitate the transfer to the 40-meter system.

Long-Term LIGO III Research in Configurations and Control

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. Other long-term development topics are:

The Sagnac Configuration: 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 tabletop 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.

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. A major step in this research will be the construction of a Fabry-Perot Michelson interferometer with injected squeezed vacuum at ACIGA/ANU.

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 will be limited by the SQL. Thereafter, any further lowering of the noise minimum will require increasing the test masses upward from 30 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. MSU and CaRT are presently active in this domain. Research on experimental prototypes will be carried out at ANU and at MIT.

Lasers and Optics Research Plan

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.

Thermal engineering

The Lasers and Optics Working Group is developing, under the leadership of Ray Beausoleil of Hewlett-Packard, an optical modeling package called MELODY that incorporates core optic heating and their subsequent optical deformations to compute the electric field at the carrier and modulation frequencies at all of the output ports of an interferometer. This model is a synthesis tool whose purpose is to aid in designing interferometers rather than studying their performance. A model has been written using MELODY routines to analyze the LIGO I interferometer and the results were consistent with its thermal design for which 6 watts of laser power at the power recycling mirror produced the best performance. A model written with the MELODY routines for the LIGO II reference design has also been written. It predicts that a factor of 8 must be obtained in the automatic core optic control system. This model is consistent with a second much simpler computer program designed to compare the level of optical distortion in LIGO I and II in the interferometer core optics. Over the next 6 months we will improve the MELODY subroutines which calculate optical distortions resulting from beam-induced heating of the beamsplitter. An effort to validate the code will continue. This effort will include an analysis of the GEO interferometer and comparison with the original GEO thermal design. Moreover, the work on core optics compensation and the operation of LIGO I and GEO I will provide a series of experimental results which can be compared to the MELODY predictions. Thus, the bulk of the effort on thermal engineering will consist of validation of the MELODY package, upgrades to the code to improve performance, and design work on LIGO II.

Core optics

During the LSC meeting at Stanford University (July 19-21, 1999), the LIGO Lasers and Optics Working Group selected sapphire for the LIGO II core optics with a backup of silica should the sapphire development program fail. Crystalline core optics offer a reduction of internal thermal noise, improved thermal conductivity and increased density. Among the hard oxide crystals that are transparent at 1064 nm sapphire, YAG, GGG and spinel are all promising. However, current measurements of Q by Braginsky and Rowan, highest thermal conductivity and the lowest absorption and most advanced growth technology put sapphire at the head of the list. There is, however, much to be demonstrated including growth in sufficiently large sizes and uniformity as well as figuring and polishing to LIGO’s exacting specifications. Nevertheless, the increase in overall interferometer sensitivity has provided a strong motivation to start development work on sapphire now. This program was begun with a meeting between LIGO and Stanford personnel and Crystal Systems staff at Crystal Systems on August 15, 1999. During this meeting a preliminary set of requirements were described and the Crystal Systems growth technology was discussed in detail.

The development of sapphire core optics for LIGO II is the single most complex and risky undertaking on the road to reaching our LIGO II sensitivity goals. This development effort, called Pathfinder II, is a collaborative effort between LIGO, Stanford University, Glasgow University and Syracuse University. The effort will be coordinated by LIGO/Caltech with the support and advice of Prof. Marty Fejer and Dr. Roger Route of Stanford University.

The Pathfinder II program will require many large sapphire samples. LIGO will take responsibility for insuring that the appropriate (in both size, number and orientation) samples are obtained in a timely manner to allow all of the development work to be done without wasting money on either unnecessary duplicate samples or using large expensive samples where smaller samples are sufficient, especially in those cases where the number of samples must be large to obtain a good statistical sample.

LIGO will make measurements of surface figure and microroughness, substrate uniformity and birefringence and coating birefringence and absorption. LIGO will take responsibility for obtaining the large sapphire samples and having them figured, polished and coated. Polishing will be carried out under the supervision of LIGO and measurements of the microroughness will be made using Atomic Force Microscopy. The substrate figure and uniformity measurements will be made at LIGO using the 1064 nm ZYGO interferometer. These measurements will be repeated after the optics are coated.

The Stanford group will take responsibility for measuring and attempting to understand the substrate absorption problem. Absorption measurements will be made at Stanford (Alexandrovski and Fejer) using Photothermal Common-Path Interferometer (PCI).

Figure 3 shows the geometry of a mirror defining the optical axis and the orientation of an as grown sapphire boule produced by the Heat Exchanger Method (HEM). For reasons having to do with thermal noise the mirror should have an aspect ratio of D/T □ 2.5. However, the HEM process produces crystals with an aspect ratio T/M □ 1. The crystal axes of the largest samples of sapphire from the HEM process are oriented with the a- or m-axes along the axis of symmetry of the boule. Smaller crystals can be grown with the c-orientation. Consequently, if the mirror must be used with the crystal c-axis along the mirror optical axis, then either substantial work must be done on c-axis growth or, what seems a better approach at this time, larger a- or m-axis crystals must be grown and mirrors bored out along their c-axis.

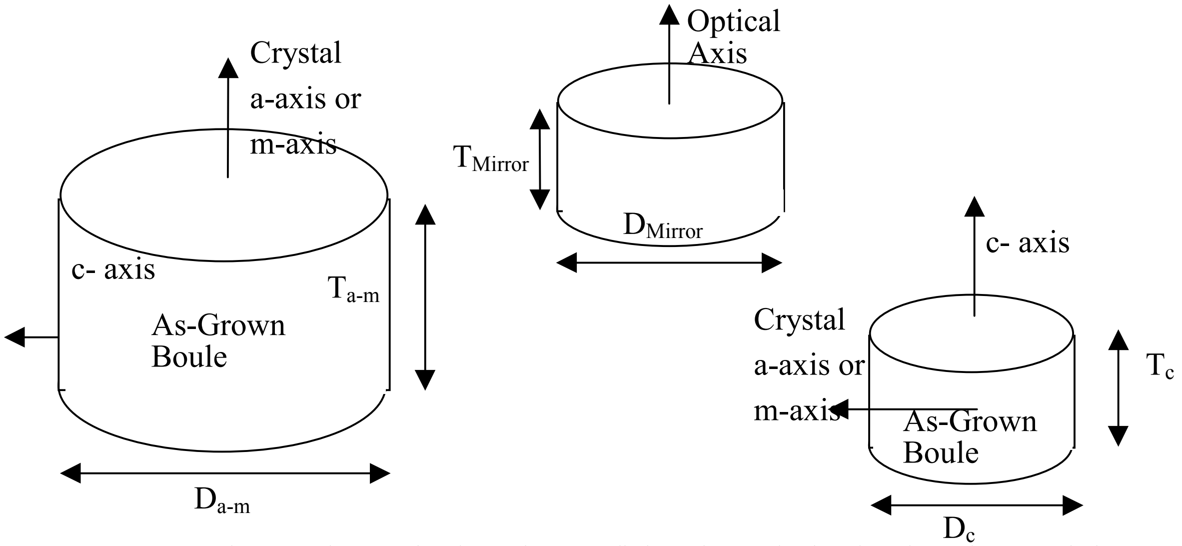

Figure 3. Mirror and crystal orientation. Defining the optical axis of a mirror and the crystal axes of two boules of sapphire from the HEM growth apparatus one c-axis and the other a- or m- axis.

A modeling effort is currently underway to determine whether the a- or m- axis orientation can be used for the core optics. If it can, the development effort required will be substantially reduced.

It may be necessary to compromise on the size of the sapphire samples due to the growth considerations. For example, it may be much easier to grow a crystal for a mirror with a reduced substrate thickness requirement from 12 cm to 10 cm while increasing the diameter to maintain the 30 kg mass.

Core optics compensation

The circulating optical power in the LIGO II interferometer will be approximately 50 times higher than in LIGO I and even a small amount of substrate and/or coating absorption can lead to significant distortion of the wavefronts and consequent loss of optical efficiency. Design and prototype testing of the sensing and thermal actuation systems will be performed at LIGO/MIT (Lawrence and Zucker). This will include finite-element modeling of the thermal response characteristics. Testing will be done using commercial Schack-Hartmann wavefront sensors and 100-mm class metrology interferometers. Projection of net uncorrected wavefront defects onto overall interferometer performance figures of merit will be done in collaboration with Stanford using the modal decomposition model MELODY, as well as the FFT wavefront propagation code developed by VIRGO, MIT and Caltech. A full-size engineering first article actuator system will be constructed and tested in the LASTI interferometer (if configured with large-waist optics) or possibly in the LIGO 250 mm core optic measurement facility. The sensing system will be independently tested by installing it as a non-invasive probe on a LIGO I dark port beam sample.

Photo detectors

The constraints of high power, high SNR, RF response, high quantum efficiency, and other optical and electronic requirements found in LIGO I do not apply for other applications of photodiodes (for example, optical communications with extremely low light levels). Hence, manufacturers have not been driven in these directions by existing communications markets and it will be necessary to develop a photodiode capable of meeting the required specifications. Rear-illuminated InGaAs PIN photodiodes offer device characteristics that are well beyond the capabilities of current off-the-shelf devices. It may be possible to develop a single photodiode (with a diameter of approximately 3 mm) that can handle roughly 10 W of power at 25 MHz. These devices offer several advantages over front-illuminated commercially available devices, such as very high quantum efficiency (>95%), linearity at higher light levels, and better thermal power dissipation facilitating an increased ability to handle high power transients. If, however, 100 MHz bandwidth is required, several smaller devices connected in parallel may be needed to meet these specifications.

The development of back-illuminated diodes will be undertaken by a collaboration of Stanford (initial device fabrication) and MIT (requirements and testing). The successful device design will then be transferred to a commercial semiconductor foundry for fabrication and packaging. After final bench testing, first article detectors will be non-invasively integrated into a LIGO I interferometer for functional testing under realistic conditions. For possible non-linearity and non-uniformity of spatial response, this will represent the most realistic form of qualification test.

Input optics

Critical development items for the input optics consist of the EOM's (phase modulators) and Faraday isolator in the input optics (IOO) system. The University of Florida and Stanford will collaborate to produce the combination of materials and optical configurations to handle the modulation needs and isolation at the high optical power of LIGO II.

Optical isolators

One or more of the schemes described in the reference design will be required to provide sufficient optical isolation. We estimate that at 100 watts, only 40% of the light remains in the fundamental Gaussian mode. Thus, thermal compensation methods such as those proposed for LIGO mirrors will be investigated at the University of Florida.

By virtue of their in-vacuum position in the LIGO optical beamline, the Faraday isolator must meet stringent vacuum requirements. In LIGO I, the magnets used to generate B-fields are composed of sintered Nd:Fe:B (T_{Curie} = 337 °C) and cannot be baked above 60 °C. While hydrocarbon outgassing rates are met for LIGO I vacuum levels (9×10^{-12} torr hydrocarbon partial pressure), this may become a severe problem for advanced LIGO where higher stored cavity powers are more sensitive to contamination. The development of sinterless magnets with higher Curie temperatures will be investigated at the University of Florida.

Mode cleaners

The circulating power in the LIGO II mode cleaner, while impressive, is still below the 5 MW/cm^2 damage threshold of high-quality coatings. Thus damage (at least in the short term) is not an overriding issue. There are, however, at least two concerns associated with the input mode cleaner.

Mode Cleaner Mirror Contamination - There is probably not adequate information about the effects of these high power densities over long (~1 year) continuous operation in ultra-high vacuum, so the possibility of slow damage and mirror contamination will be investigated at the University of Florida.

Thermal Lensing - Thermal deformation of the model cleaner cavity comes about from both coating and substrate absorption. Thermal lensing in the mode cleaner mirrors will occur at power levels well below the damage threshold, and methods for mitigating this will need to be investigated. These methods could involve both new optical configurations and improved materials (e.g., sapphire, coating technology improvements). We have used a thermal model to estimate the amount of thermal lensing in a triangular mode cleaner for both LIGO I and LIGO II power levels assuming a 1550 finesse cavity (baseline for LIGO I) with fused silica mirrors.

Based on this model, thermal lensing distortion of the mode cleaner optics is not expected to affect mode cleaner performance. However, coating absorption and absorption due to surface contamination are not included in the model. To investigate these effects, a cavity will be set up at the University of Florida which simulates LIGO stored power levels. Deformation of the cavity can be measured by monitoring the relative shift of the resonant frequencies of the fundamental and first higher order cavity modes as a function of stored power. The current substrate material is fused silica; sapphire will be considered if optical or mechanical considerations require it.

Output Mode Cleaner - The present design for LIGO II does not contain an output mode cleaner. If indicated by more detailed models or by LIGO I experience, a development effort will be established at the University of Florida.

Lasers

The path from LIGO I to LIGO II will require increasing laser power. This will involve the development of diode laser pumped slab optical gain media that can be used either as injection locked power oscillators or as a multi-pass power amplifiers. Moreover, LIGO III interferometers may have entirely new interferometer configurations that could, for example, demand low temporal coherence sources to minimize scattered light effects or shorter wavelengths. Thus the laser development program must not only meet the LIGO II requirements, but be sufficiently broad to lay the foundation for LIGO III. The work on high power lasers will be centered at Stanford and at Adelaide University.

Frequency noise

Frequency noise in diode laser pumped solid state lasers is dominated by 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 amplifier systems which use several high power diode lasers usually have a frequency noise spectrum dominated by the master oscillator. The investigation of feedback control schemes to reduce laser frequency fluctuations will be carried out by Adelaide University, GEO/Hannover, LIGO and Stanford and the frequency noise from high power sources will be measured.

Amplitude noise

The amplitude noise at low frequency in oscillators and amplifiers is largely determined by the gain fluctuations resulting from the diode laser power fluctuations while free running oscillators have relaxation oscillation peaks in the tens to hundreds of kHz frequency range. These relaxation oscillations can be eliminated by feedback from the output of the laser to the diode laser current or by injection locking with a master oscillator in which the relaxation oscillations have been suppressed. At high frequencies the gain saturation and mode discrimination of an injection-locked oscillator has an advantage over a MOPA, as the MOPA requires a post-amplification Fabry-Perot interferometer, a mode cleaner, to spatially and temporally filter the beam to the shot noise limit at the photo-current on the main signal detector. The amplitude noise reduction system could include a measurement of the laser output power fluctuations and feedback to a small set of the diode pump lasers in one of the amplifiers to reduce low frequency amplitude noise. This work was begun at LIGO/Caltech on the LIGO I MOPA and will be continued by that group, GEO/Hannover and Stanford on high power sources.

Injection-locking control systems

An alternative to the MOPA is an injection-locked oscillator (used e.g., in the VIRGO interferometer). Work will concentrate on improving the reliability of the injection-locking server by using a multi-stage system in which each stage provides a relatively small power gain and thus has a larger locking range. This work will be carried out by Adelaide University and GEO/Hannover.

Unstable resonators

Unstable resonators are often used in high power lasers and are being investigated for LIGO II. Their large optical mode volume overlaps efficiently with the gain medium to offer much better power scaling than in a stable resonator laser and higher efficiency than an unsaturated MOPA. In a properly designed unstable resonator, the output consists of a single transverse mode which can be matched to a stable resonator with high efficiency (>98%). Development work on unstable resonators is underway and will continue at Adelaide University where measurements of frequency and amplitude noise will be made on a high power injection locked laser.

Master Oscillator Power Amplifier (MOPA)

Low noise master oscillators followed by high power amplifiers is a common approach to power scaling which preserves the low frequency noise of the master oscillator while increasing the linear spectral density of amplitude noise roughly as the power amplifier gain. However, to achieve high efficiency the MOPA must be operated in a highly saturated regime and while the noise in unsaturated systems has been measured at Stanford and is well understood theoretically the noise of such free space saturated systems is not understood. This noise is being investigated by LIGO/Caltech and at higher power by the Stanford Group.

Pre-stabilized laser

The development work on the pre-stabilized laser will be carried out at LIGO/Caltech and LIGO/Hanford and GEO/Hannover. The work involving aspects of the high power systems will be done in collaboration with the groups at Adelaide University and Stanford University.

Long-term LIGO III Lasers and Optics Research Program

Diffractive Optics

LIGO II will require a circulating power in excess of a 10 kilowatts on the beamsplitter and LIGO III may 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 thicker (more massive) 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 that 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. This work is being carried out at Stanford.

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 hydrocarbon film onto a core optic or mode cleaner mirror can increase surface roughness and optical absorption. This 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 photochemical interactions the absorption of these contaminating layers at a particular wavelength and optical intensity can only be determined empirically.

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 photochemistry 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.

Higher power lasers 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. The difference in wavelength between the two lasers has no practical consequence for either LIGO optics coatings, substrate absorption or for nonlinear frequency conversion. In addition, there is substantial commercial interest driving the development of both Yb lasers and their pump diodes for very high power applications. The Stanford group is involved in this work where a 100 W laser is under development.

Shorter wavelength lasers

Shorter laser wavelengths than the present 1064 nm offer several potential advantages: reduced beam size (allowing practical sizes for delay line mirrors), and increased displacement sensitivity. The highest average power demonstrated for 532 nm output is 200 W in a Q-switched system while commercial products operate at 5-10 W of 532 nm output with reliability suited to research applications. Work is only now underway to develop 1 W output at 355 nm and 266 nm for commercial applications. If the choice is made to move to shorter wavelengths there are two choices: resonant harmonic generation in a ring cavity or single pass harmonic frequency conversion in a quasi-phase-matched material. The highest power resonant frequency conversion was in an LBO doubler and converted 19 watts of 1064 nm radiation to 12 watts at 532 nm light. The highest power single pass doubling was done in periodically poled lithium niobate and converted 5 watts of 1064 nm to 2.5 watts of 532 nm. Neither of these materials shows much promise for the second stage of frequency conversion to the UV. At present the only candidate materials for this conversion step are BBO and periodically poled quartz both of which will require considerable development. This work is underway at Stanford.

Delay line core optics and cryogenic operation

Clear goals for LIGO III are reduced radiation pressure noise and reduced internal thermal noise. One path involves using cryogenics to reduce the thermal noise, and much more massive mirrors to reduce the radiation pressure noise. Delay lines are one interesting option, as their larger mirrors have the virtue of greater mass. The use of nontransparent materials opens the possibility of using silicon as the test mass. Silicon's high thermal conductivity (4 times that of sapphire), and the ability to grow large high quality crystals makes it an attractive candidate for cryogenic delay line applications. Work on delay lines and crystalline optics is currently underway at Stanford.

Suspension and Isolation Research Plan

Suspension Research

The primary role of the suspension is to realize the potential for low thermal noise, and much of the research into suspension development targets our understanding of the materials and processes to realize this mission. In addition, there are design efforts to ensure that the seismic attenuation and the control properties of the suspension are optimized, and prototyping efforts to ensure that the real performance is understood.

The test mass thermal noise (with a gentle $f^{-1/2}$ frequency dependence) limits the ability to profit from changes in the optical configuration and from reductions in the shot noise in general. The suspension thermal noise (roughly a $f^{-5/2}$ frequency dependence) 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. To realize the reference design, the following lines of research must be pursued: Test mass materials and suspension fiber development and mechanical integration, studies of excess noise, and tests of prototype suspensions.

Test mass materials development

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 and sapphire components and assembled systems, to guarantee that we can reach the levels limited by the best material properties. (This effort is carried out in parallel with the sapphire development effort described in the Lasers and Optics section of this document.) These measurements will be performed by the standard technique of measuring resonance quality factors to obtain information at the resonant frequencies (Stanford, LIGO/Caltech, GEO), and by the 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 and GEO; a planned collaboration with Iowa State will develop means to calculate the noise from localized losses and arbitrary shapes.

Test mass mechanical integration, suspension fiber development

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. GEO, LIGO/Caltech, and JILA plan production of fused silica fibers (cylindrical and ribbon), 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.

Excess noise studies

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 will be made by measuring the statistics of the thermal excitations of, for example, wire resonances, as pioneered at Moscow. State University (MSU). 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 the Thermal Noise Experiment (TNI) at LIGO/Caltech concentrating on the internal test mass noise (other efforts are in VIRGO and ACIGA, addressing pendulum thermal noise). A facility is being constructed at LSU to measure creep and creak in mechanical connections and assemblies which will aid in both developing design rules and testing specific solutions. Elastic creep as an indicator of excess noise is being studied at LIGO/Caltech, and the JILA isolation testbed will be characterized to understand excess noise in active systems.

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).

Suspension Subsystem Development

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.

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 the suspension as installed in GEO 600. As prototypes are developed to demonstrate component and attachment techniques (GEO, Stanford, LIGO/Caltech) they too will be characterized. A specific effort to characterize motion cross-couplings due to imperfections will be undertaken at PSU. 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} due to the curvature of the Earth, but may well enter more strongly due to asymmetries of the suspension.

Isolation and Controls Research Plan

The isolation system provides filtering in the observation band and at lower “control” frequencies. The development effort is to first explore several means to this end, choose a unified concept, and then to follow with a rapid design and test.

Isolation subsystem development

The multiple-pendulum ‘soft’ system is under study at LIGO/Caltech. Improvements and simplification of the vertical isolation will be studied on a several-stage prototype at Caltech. The active ‘stiff’ isolation system is being developed at JILA, Stanford, LSU, and MIT with prototyping to be performed in the Stanford Engineering Test Facility (ETF). An evaluation procedure to select a design for LIGO II has been put in place, and a choice will be made in the first quarter of ’00. At that time all participants will concentrate on the single design, bringing the expertise in control and mechanical design to bear on the development of an engineering prototype, which will be installed in the LIGO/MIT LIGO Advanced System Test Interferometer (LASTI).

In addition to the design of new components for LIGO II, it is of great value to characterize the LIGO I isolation subsystem. Our models need to be improved, especially those related to quantifying and understanding cross-coupling. As our understanding of this subsystem 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.

Controls development

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. In addition, specific technical solutions will be explored to find processors, analog interfaces, and software systems which are robust, reliable, and flexible and thus appropriate for installation in LIGO.

Our Controls Research effort will involve analyzing these issues, and helping to determine mechanical configurations and control topologies that meet the overall suspension design goals for LIGO II. This work will primarily be carried out by LSU, Stanford, JILA, and LIGO/Caltech/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.

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 LIGO Advanced System Test Interferometer (LASTI). The specific configuration of suspensions and the optical system will be chosen to best illuminate the design performance. One of the primary purposes of these tests will be to validate the models that we are using for the design of the more complex controllers/mechanical systems.

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 that limits the impact on the “downtime” of LIGO. The LASTI will play a central role in these tests.

Specific tests planned are:

- controls tests of prototype isolation systems (ETF). This will involve installing and testing scale model isolation prototypes and testing for acquisition and operation;
- controls/isolation tests of advanced ‘hexapod’ high-gain sensor/actuators (ETF);
- transfer function tests of engineering prototype isolation systems (LASTI). A full-scale isolation system will be installed in a LIGO vacuum equipment chamber with LIGO interfaces, and the net isolation and control characteristics of the assembly measured and iterated as needed;
- noise performance tests of prototype suspensions (LASTI). 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 (LASTI). First articles of the LIGO II mechanical system will be installed in the LASTI to ensure minimum downtime for the upgrade of the LIGO site interferometers.

Additional tests for any of the LSC System Test Facilities (ETF, 40 m, LASTI) may become evident as the research proceeds.

Before either the ETF or the LASTI 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, readout, and control 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.

Long-term LIGO III Suspension and Isolation Research Program

Suspensions/Thermal Noise

Thermal noise research has indicated possible further improvements that could only be ready for LIGO III. 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; preliminary measurements of material loss properties look promising. Silicon also has very low dissipation levels, and might be a candidate for applications not requiring transmission through optics, e.g., diffractive configurations (Stanford, CEGG). Alternatives to fiber suspensions (e.g., magnetic or electrostatic) may lead to reduced thermal noise (CEGG).
- 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 and CaRT 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.

Isolation and Controls

Advanced research aimed at LIGO III will also be carried out on several other approaches which address controls issues in different ways. 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.

The proposed LIGO II isolation system should allow facility-limited performance for frequencies higher than ~10 Hz. Improvements in isolation for LIGO III would be driven by observation or prediction of sources which had signal strengths above the Newtonian background at frequencies lower than 10 Hz. 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 (CaRT). This may lead to means to reduce this noise source for the most advanced interferometer designs. Continued seismometer development at JILA will be targeted at the required sensors for this approach if indicated.

Activities Tables

The manpower data cover both NSF and non-NSF (universities, international collaborators) resources and are intended to show the scale of the effort.

Configurations and Controls Working Group

Activity	**Participants**	**Deliverable**	**Approximate Manpower (FTE)**	**Milestones**
Sensing and Control Scheme Development and System Optimization	ACIGA/ANU, Caltech/LIGO, GEO, **MIT/LIGO**, U. of Florida	Identification and modeling of sensing concept Identification and design of length and alignment control Bench-top tests of control alternatives Selection of a system to meet the Science goals	99: 7 00: 5 01: 4 02: 3	1Q00: Conceptual design review 2Q00: Options review 3Q00: Down-selection 2Q01: **ISC DRR** 3Q01: Optics specification 3Q02: **ISC PDR** 4Q02: Prototype test review 4Q04: Engineering test review
Science Prototype Test (Response, Control, Readout, Noise, Lock-Acquisition)	**GEO**, U. of Florida	Operation and evaluation of a 10 m signal tuned interferometer with arm cavities	99: 5 00: 7 01: 7 02: 5	4Q01: Interim review: basic signal recycling 3Q02: GEO prototest review: noise analysis
Control Prototype Test	**Caltech/LIGO**, GEO, U. of Florida	Robust operation of 40 m signal tuned prototype with final LIGO compatible control system	99: 4 00: 4 01: 4 02: 6	2Q00: 40 m vacuum and isolation systems complete 3Q00: 40 m design of optics/electronics complete 1q-1: 40 m suspensions, laser systems complete 1Q02: 40 m initial shakedown complete 3Q02: 40 m prototype operational 4Q03: control implementation review 4Q03: **ISC FDR** 4Q04: Engineering test review: reliability
LIGO III Groundbreaking Research	ACIGA/ANU, CaRT, MIT/LIGO, MSU, Stanford Univ.	Feasibility studies of means to improve optical sensing ANU, CaRT, GEO, MIT, MSU: Squeezing and QND methods Stanford: delay lines, Sagnac interferometers GEO: advances in signal recycling methods	99: 0 00: 2 01: 3 02: 4	

Laser and Optics Working Group

Activity	**Participants**	**Deliverable**	**Approximate Manpower (FTE)**	**Milestones**
Core Optics Development	**Caltech/LIGO**, Univ. of Glasgow, Stanford Univ.	Figure, polish, uniformity Absorption, bonding	99: 4 00: 7 01: 10 02: 13	**4Q99: COC DRR**, initiate polishing, coating, metrology **3Q01: COC PDR** 1Q02: Substrate material selected (all types) **2Q02: COC FDR**/Pathfinder II process complete
Core Optics Compensation	HP, **MIT/LIGO**, Stanford	Factor of 8 reduction in distortions	99: 1 00: 1 01: 1 02: 1	1Q00: Initial experiments complete 4Q00: Thermal modeling mature 1Q01: Sapphire tests complete
Thermal Modeling	Caltech/LIGO, **HP**, MIT/LIGO, Stanford	MELODY program and modifications as requested by LSC	99: 1 00: 1 01: 1 02: 1	Status reviewed at biannual LSC meeting
IO: Mode Cleaners & Telescopes	**U. Florida**, Caltech/LIGO	Mode cleaner, telescope and mode matching optics for 180 W laser with required laser noise	99: 1 00: 2 01: 3 02: 3	**4Q00: IO DRR/** MC conceptual design, thermal modeling complete 2Q01: Length and alignment sensing and control design **4Q01: IO PDR** 2Q02: Substrate selection/Initiate procurement of mode cleaner substrates, polishing, coating **4Q02: IO FDR**
Ancillary Optics- PM Isolators and Photodiodes	**U. Florida**, Caltech/LIGO, Stanford	High power phase modulators 180 W optical isolators 8 Watt 25 MHz photodiodes	99: 1 00: 2 01: 2 02: 4	3Q00: Demonstration of isolator (<35 dB) at 50 W 4Q00: Modulator at 100 W decision 1Q01: Phase modulation components ordered 2Q02: Demonstration of prototype PM Method 3Q02: Prototype suspension design for isolator 4Q02: Thermal lensing compensation results and decision on placement of isolator
Photodiodes	**MIT/LIGO**, Stanford	8 W, 25 MHz photodiode design and prototype	99: 1 00: 1 01: 2 02: 2 03: 2	4Q00: Demonstration of 100 mW detector 4Q01: Specifications defined 4Q03: LIGO II prototype detector fabricated, characterized

180 W Laser	Hanford/LIGO, Caltech/LIGO, ANU, **Stanford**	Design for 180 W diode pumped Nd:YAG Laser; 100 W prototype	99: 5 00: 5 01: 5 02: 5	**4Q00: Laser DRR**/100 W demonstration **2Q01: Laser PDR**/Downselect **4Q01: Laser FDR**
Pre-Stabilized Laser (PSL)	Caltech/LIGO, **Hanford/LIGO**, Hannover-GEO, Stanford	Design for PSL system	99: 1 00: 1 01: 2 02: 3	**4Q00: PSL DRR** **1Q02: PSL PDR**/Downselect **2Q03: PSL FDR**

Suspension and Isolation Working Group

Activity	**Participants**	**Deliverable**	**Approximate Manpower (FTE)**	**Milestones**
Test Mass Materials Development	Caltech/LIGO, GEO, **Stanford**, Syracuse	Identification, development, and test of test mass materials (mechanical/thermal noise properties)	99: 2 00: 5 01: 4 02: 4	4Q00: Losses of target materials determined 1Q02: Selection of LIGO II test mass material 4Q02: Characterization of specific selected material
Test Mass Mechanical Integration	Caltech/LIGO, **GEO**, Stanford, Syracuse	Initial design and performance prediction for test masses as installed; coating and attachment issues	99: 5 00: 6 01: 2 02: 2	3Q00: Bonding/welding technique defined 4Q00: Impact of coating assessed 3Q01: Actuators certified for thermal noise impact 4Q02: Characterization of specific techniques
Suspension Fiber Development	Caltech/LIGO, **GEO**, JILA, Stanford, Syracuse, MSU	Initial design, fabrication, and performance prediction for suspension fibers	99: 4 00: 3 01: 1 02: 1	2Q00: Ribbon conceptual design 4Q00: Silica ribbons/fiber research completed 2Q01: Fiber fabrication process established 4Q02: Characterization of production fibers
Excess Noise Studies	**Caltech/LIGO**, JILA, MSU, Syracuse	Performance prediction and experimental characterization of suspension noise beyond thermal noise; suspension design guidance	99: 4 00: 6 01: 5 02: 4	2Q00: TNI first lock 2Q01: TNI studies on LIGO I completed 2Q01: TNI fused silica suspensions installed 4Q01: Characterization of fiber excitation 1Q02: TNI initial fused silica results 1Q03: TNI final fused silica results
Isolation Subsystem Development	Caltech/LIGO, JILA, LSU, MIT/LIGO, Stanford	Initial isolation system design and performance prediction; engineering isolation prototype	99: 7 00: 7 01: 8 02: 5	3q99: initial requirements draft 4Q00: mid-course concept review 2Q00: Isolation conceptual design adopted **3Q00: SEI DRR** **1Q01: SEI PDR** 3Q01: engineering prototypes fabricated 3Q02: prototype quantities contracted out **3Q03: SEI FDR** 1Q04: first article fabricated

Suspension Subsystem Development	CEGG, **GEO**, Caltech/LIGO, MIT/LIGO, Penn State, Stanford	Initial suspension design; engineering suspension prototype	99: 6 00: 6 01: 5 02: 5	1Q00: Install first GEO-600 suspension 2Q00: Install first fused-silica GEO-600 susp. **2Q00: SUS DRR** 1Q01: Downselect cylindrical/ribbon fiber 2Q01: Complete GEO-600 susp. install **4Q01: SUS PDR** 4Q01: Engineering prototype fabricated **3Q03: SUS FDR** 1Q04: First article suspensions fabricated
Controls Development	Caltech/LIGO, GEO, LSU, MIT/LIGO, **Stanford**	Initial design for mechanical controls hierarchy; controls prototype	99: 1 00: 1 01: 1 02: 1	1Q00: Controls hierarchy developed 4Q00: Controls concept developed 2Q01: Controls prototype bench tested 1Q02: Controls prototype installed in LASTI
System Tests	Caltech/LIGO, GEO, LSU, **MIT/LIGO**, Penn State, Stanford, Syracuse	End-to-end tests of prototype suspension and isolation system performance	99: 1 00: 5 01: 5 02: 2	4q99: LASTI envelope commissioned 1Q00: LASTI external structures installed 2Q00: LASTI infrastructure design review 3Q01: LASTI infrastructure complete 1Q02: LASTI prototype installation complete 3Q02: LASTI locked 1Q03: LASTI controls test review 2Q03: LASTI noise prototype installed 3Q03: LASTI noise performance test review 1Q04: LASTI final test review 1Q04: LASTI first article installation starts 3Q04: LASTI first article tests complete
LIGO III Groundbreaking Research	CEGG, GEO, LSU, Stanford, MSU	Feasibility studies of means to approach facility limits	99: 1 00: 1 01: 1 02: 3	

APPENDIX: LIGO II DETECTOR REFERENCE DESIGN

Introduction

This Appendix contains a description of the LIGO II Detector Reference Design that the LIGO Scientific Collaboration (LSC) and LIGO Lab have developed. The LSC plan for executing the required R&D is found in the body of the 1999 LSC White Paper on Detector Research and Development (of which this document is an appendix). The LIGO Laboratory Conceptual Project Book (LIGO-M9900288) describes the conceptual program to carry out the fabrication, installation, and commissioning of this Reference Design.

Configuration/Controls

Both LIGO I and LIGO II use an adapted Michelson interferometer to detect the strains in space due to gravitational radiation. The mirrors and beamsplitter are suspended as pendulums in a vacuum enclosure to reduce extraneous forces and apparent motions due to air density fluctuations. Multiple reflection of the light along each arm of the interferometer, achieved via Fabry-Perot cavities, increases the interaction time with the gravity wave and thus the signal size. Poissonian photon-counting limit the sensitivity of the interferometer, an effect which is reduced by increasing the light energy (number of photons) stored in the arm cavities. The low loss optical system can be enclosed within an overall “power recycling” cavity in which the circulating laser power is maximized. A complementary sensitivity limit is the Poissonian quantum radiation pressure force which disturbs the mirrors from their equilibrium position. The balance of the photon counting and quantum radiation pressure noise produces the standard quantum limit for the interferometer, a true limit performance if a classical measurement technique is used.

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, as in the power recycled case. An 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 necessary for control of the interferometer. This configuration is sketched in Figure A1.

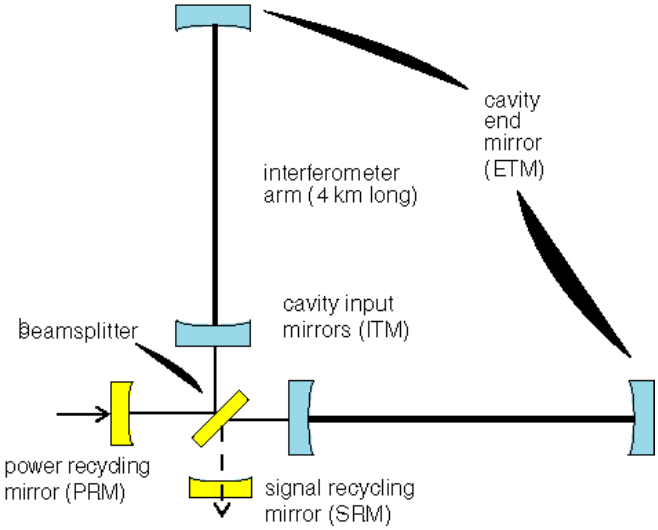

Figure A1. Signal- and power-recycled Fabry-Perot Michelson optical configuration

The new configuration will share much of the basic concept with the initial LIGO detector, using related modulation and signal measurement systems. The research will clearly benefit from the experience gained in the design, installation and test of the initial LIGO detector. The experiences in the first full-scale trials of a signal recycled interferometer in the GEO 600 facility, albeit it of a different configuration than that to be placed in the LIGO, will also guide the program.

Configuration Reference Design

A signal-recycling mirror is placed between the normal output port of the power-recycled Fabry-Perot Michelson interferometer and the photodiodes that normally detect the output light. Just as the “power recycling cavity” can be said to exist, we can now validly use the term “signal recycling cavity” to describe the resonant system formed by the power recycled Fabry-Perot Michelson and the signal recycling mirror. When the interferometer is at the nominal dark-fringe operating condition with the power recycling cavity resonant, the signal recycling mirror works with the two cavity input mirrors (ITM, for “Inside Test Mass”) to form another cavity which determines the transfer function from the signal field in the arms, produced by gravitational radiation, and the signal field at the main photodiode. In this way careful choice of the cavity input mirrors and signal recycling mirror transmittances allows the bandwidth of the interferometer to be determined. The position of the signal recycling mirror, on a sub-wavelength scale, then influences the tuning of the interferometer (and in some cases can further alter the bandwidth).

In systems where the bandwidth is substantially reduced from the non-signal recycled case this technique is called *dual recycling*, while when the bandwidth of the high finesse Fabry-Perot arm cavities is increased it is called *resonant sideband extraction*. The curvature of the signal recycling mirror is selected to ensure that the cavity formed by this mirror and the main interferometer is stable. In this case the gross amount of light falling on the detector may be reduced while the signal sidebands are enhanced. Best broad-band performance is obtained in the latter mode of operation.

The minimum bandwidth is determined by the total optical loss in the interferometer, and is obtained when the signal and power recycling mirrors have the same reflectivity, matched to the loss. This requires a 2% transmitting signal recycling mirror while the broadest useful response requires a mirror which transmits about 35%. Reasonable coverage of the possible response shapes can be obtained by having the signal recycling mirror chosen from a set of 4. To avoid a significant loss of observation time these mirrors would have to be already suspended in the vacuum system with a mechanism for selecting and positioning one. This is likely to be a complex and possibly slow process, probably taking several days.

An attractive alternative is to employ a variable signal recycling mirror. This can be done by using a pair of mirrors or a solid étalon to replace the single component. If two separate mirrors are used each on its own suspension the additional complexity in length and alignment sensing and control may be considerable, and this option will be investigated as part of the LIGO III program. The use of a solid étalon made of fused silica has been proposed for GEO 600, and it should not be too difficult to adapt this technique for LIGO. The étalon is made of fused-silica with the 'front' surface (that which faces the beamsplitter) being more reflective than the 'rear'. The front may be thought of as determining the mean reflectivity of the étalon as a whole and the rear as determining the range of reflectivity as the étalon is tuned though a fringe. The combination of thermo-refractive and thermoelastic effects in silica ensure that a small temperature change (of order 1 °K) is enough to scan the étalon through all possible values of reflectivity. The thermal properties of the material provide a time constant of order hours. Temperature control would be achieved through a combination of regulation of the environment, and a small amount (<100 mW) of thermal radiation supplied from a rapidly adjustable source (such as a lamp). Sensing and control is much simplified with this method since there is just one, pre-aligned component. Any available response can be obtained and stabilized within a few hours using this method.

Length and Alignment Sensing and Control

The sensing system that is used to read-out the main interferometer length degrees of freedom will be modified from that used in LIGO I to allow efficient operation with signal recycling. The most important degrees of freedom are the differential and common mode arm lengths, the Michelson path difference and the lengths of the two recycling cavities. The gravitational wave information is associated with the first of these, and this must be read-out with the highest fidelity.

The baseline proposal for the sensing system is a modest development of the technique used in LIGO I. Alternative techniques (specifically the use of no modulation for the main read-out, modulation applied after the light exists the interferometer, or modulation that is resonant in at least one of the arm cavities) are also under evaluation to discover whether they will provide enhanced resistance to the effects of thermal lensing in the core optics. Such alternatives would only be considered if they considerably relax thermal or control noise requirements.

Baseline length sensing method

The light from the laser is modulated at 3 frequencies and light from the interferometer is analyzed at 3 points: the main output from the detector, the light reflected from the power recycling mirror and a small fraction of the light picked off inside the power recycling cavity. The signal from the main output provides information mainly about the differential armlength. The other necessary information will be obtained using linear combinations of the signal obtained at the 3 ports, in a manner very similar to that used for LIGO I. By taking (some) linear combinations of the signal from 3 ports, 3 modulation frequencies and 2 quadratures at each demodulation, all of the necessary signals can be constructed. (Alignment information is obtained in an exactly parallel manner using two quadrant photodetectors at each of the 3 ports, as in LIGO I.)

To obtain near-optimum signal to noise ratio for the interferometric measurement it is necessary to ensure that the modulation sidebands at the main output of the detector strongly dominate over any waste light. This can be satisfied if the interferometer fringe contrast is good and the transfer of modulation sidebands from their point of application (before the mode cleaner) to the output is efficient. (In narrow-band operation just one sideband will be efficiently transferred.)

Efficient transfer of modulation sidebands can be achieved by ensuring that they are resonant in the coupled cavity formed by the two recycling cavities. For a given modulation frequency the relevant cavity lengths (the distances from the beamsplitter to the 4 mirrors around it) must be chosen appropriately. Several solutions have been found, all very closely related but with varying minor advantages and disadvantages (such as the required modulation frequencies, the ease of separating the signals, or the precision with which optics must be positioned).

The position of the signal-recycling mirror determines the tuning frequency of the interferometer (frequency of peak optical system response). An additional modulation is required to sense the position of the signal recycling mirror, but the noise performance does not need to be as good as for the main differential length sensing. The light picked off from inside the power recycling cavity would be used to obtain the necessary error signal, in a manner similar to the method developed for GEO 600. Feedback to control the position of the signal recycling mirror will be done analogously to feedback to control ITM and ETM positions. There are no new techniques required here as the types of modulation and pick-off ports are similar to those provided for a basic PRFPM as in LIGO I.

Sensing of the other degrees of freedom is done in a manner closely analogous to the methods used in LIGO I. The baseline sensing method is presently undergoing testing on prototypes.

Length and alignment control (feedback) will be more complex than in LIGO I: to obtain the full benefit of the triple pendulum design a three way frequency-split feedback solution is proposed. This makes the task of achieving high gain in the control band with minimum actuation force applied to the mirrors considerably easier.

Table A1. Significant parameters for the configuration/control reference design

Controlled lengths	Arm differential length (GW signal) near-mirror Michelson differential length common-mode arm length (frequency control) recycling cavity resonance signal recycling mirror control
Main differential control requirement	10^{-14} m RMS
Shot noise limited displacement sensitivity	3×10^{-21} m/$\sqrt{\text{Hz}}$
Arm cavity storage time	1.8 msec
Signal recycling factor	0.25 to 4

Lasers and Optics Reference Design

Introduction

In this section we describe the LIGO II reference design Laser and Optics subsystems. There are several substantial differences from the LIGO I design:

- Replacment of the 25 cm diameter, 10 cm thick, 10 kg silica Fabry-Perot with sapphire mirrors which are 28 cm in diameter, 12 cm thick and have a mass of 30 kg. (Figure A2 below shows the interferometer topology and the locations of these mirrors.) sapphire was selected for the test masses because of its low acoustic loss (1/30 that of silica) and hence lower thermal noise, high thermal conductivity (33 times that of silica) which allows it to dissipate higher absorbed power over a larger volume than silica, and the promise of obtaining 30 kg optics which are required to maintain low radiation pressure noise at the high circulating power of LIGO II.
- Incorporation of a core optic measuring and heating system to automatically compensate for the thermo-optic distortions of the Fabry-Perot mirrors resulting from the laser beam absorption and subsequent thermo optic distortions.
- Replacment of the 10 watt LIGO I laser with a 180 W diode laser pumped Nd:YAG laser. The upgrading of the laser from 10 W to 180 W is necessary to provide good sensitivity at high frequency (f>200 Hz) where the interferometer noise is dominated by shot noise which scales as $1/\square P_{circ}$.

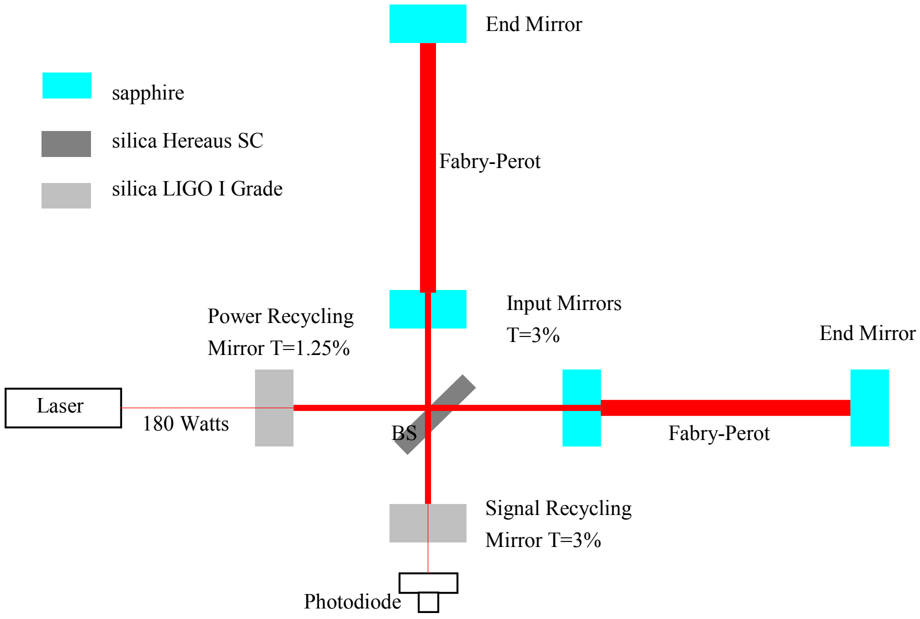

Figure A2. Laser and Optical system for LIGO II.

Core Optics

The core optics in a LIGO interferometer include the Fabry-Perot input and end mirrors (these are the mirrors which make up the interferometer arms), the beamsplitter, and the power and signal recycling mirrors. In LIGO I all of the mirrors and the beamsplitter are made of fused silica. The LIGO II reference design uses Fabry-Perot arm mirrors made from sapphire with all of the other optics made of fused silica. Figure A2 shows the materials selected for the various optical components. The choice of sapphire for the test masses offers significant performance advantages in thermal noise, but it also requires significant development; a “fall-back” option to use fused silica is, however, retained. The test masses are 28 cm in diameter and 12 cm thick but with two flats ground and polished into the sides to provide a bonding surface for attaching the suspension fibers. The beamsplitter will be made of the best available low absorption fused silica, and the power recycling mirror and signal recycling mirror, of LIGO I-class fused silica. The fused silica core optics are LIGO I sized. The mirror curvatures are similar to those of LIGO I, the transmission of the recycling mirror is about 2 times smaller than in LIGO I at 1.25 %, and the input test mass transmissions are both 3%.

Surface Figure and Polish

We have computed the requirements for the LIGO II core optics with the input power to the power recycling mirror taken to be 125 watts with a power recycling factor of 80. Table A2 shows the LIGO I and II figure and microroughness requirements, along with the best obtained to date in silica. The LIGO II micro-roughness has been demonstrated in silica in full size samples and in sapphire on small samples while the long-wavelength figure has only been shown in silica. The measured small-sample bulk absorption in sapphire meets the specifications, and present-day coatings when applied to silica have an absorption that meets the LIGO II requirements. The same coating material has been used in “supercoating” small sapphire mirrors but has not yet been tested on full-size sapphire test masses.

Absorption in Substrates and Coatings

A model has been developed which takes as input the losses (scatter, absorption) in the substrates and coatings of the core optics as well as the fixed figure losses in the Fabry-Perot cavities and computes the thermal performance of the interferometer. The LIGO II absorption requirements in the substrate and coating were estimated and the results are shown in Table A2. The sapphire substrate is required to absorb no more than 40 ppm/cm, which equals the best measurements obtained in small sapphire samples available today. The requirements on substrate and coating absorption were set by requiring no more than the level of thermo-optical wave front distortion than obtains in LIGO I be present in LIGO II after active core optic correction by a factor of 8. The coatings are assumed to be the best presently observed coatings on silica.

Table A2. Sapphire figure, bulk and coating absorption requirements.

	LIGO I Requirements (fused silica optics)	LIGO II Requirements (sapphire optics)	Best to date Small silica samples
Surface Figure	1.0 nm RMS	1.0 nm RMS	0.5 nm RMS
Micro-Roughness	0.5 nm RMS	0.25 nm RMS	0.2 nm RMS
Sapphire test masses	LIGO I , silica	LIGO II , sapphire	Best to Date
Substrate Absorption	5 ppm/cm	40 ppm/cm	40 ppm/cm
Coating Absorption	0.5 ppm	1.0 ppm	0.5 ppm
Optical Homogeneity		40 nm P-V	40 nmP-V[3]

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[3] This result was obtained in small sapphire samples.

Core Optics Compensation

Interferometer performance above a few hundred Hertz is limited by shot noise, which is fundamentally determined by the optical energy that can be stored in the interferometer. Were it not for the absorption in the core optics, the optimum power would be determined by the equilibrium of shot noise and the radiation pressure noise on the test masses. However, the optical absorption in the input mirror coatings and substrate and the beamsplitter limit the usable circulating power via distortion of the optical wavefront. Analysis shows that the LIGO II signal and power recycled interferometer requires a factor of 8 active core optics compensation to produce the same workable level of thermo-optic distortion as is found in LIGO I. In addition, spatial non-uniformity in coating or bulk absorption may induce non-axisymmetric wavefront distortions. As a result, a spatially addressable thermal actuation means, with spatial resolution smaller than the Gaussian mode diameter will be incorporated. In this system wavefront errors are sensed by analysis of the interferometer differential and common-mode output port and cavity pickoff. It is then possible to introduce a thermal component that cancels virtually any form of distortion. Indeed, even initial figure distortions unrelated to laser beam thermal loading may be compensated. These corrections are transformed into an orthonormal actuation basis and applied by modulating the intensity and dwell time of a moderate-power mid-infrared laser beam scanned across the core optic surface, selectively depositing heat in specific zones in proportion to the net local error. Actuation on only two of the main transmissive optics (for example, the cavity input couplers) should be adequate to cancel the net sum of errors in all transmissive optics. An additional corrective element in the input chain (e.g., the mode cleaner output coupler) can also be used to cancel gross errors introduced in the small-beam optics. The actuator employs either a carbon dioxide laser or a solid-state laser operated near an IR absorption band of the core optic substrate. Approximately 5 to 50 watts of mid-infrared power will be required, depending upon the amount of 1064 nm absorption.

Photo Detector

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. These specifications are shown in Table A3 below. LIGO II will probably use a rear-illuminated InGaAs PIN photodiode structure. This inverted structure significantly reduces the stray dissipation contributed by the ohmic contact, which limits SNR in ordinary front-illuminated devices. The structure also reduces thermal resistance between junction and heat sink. As a result we expect a single 3-mm diameter device to handle up to 10 W CW without damage and with adequate signal-to-noise ratio for operation at 25 MHz. For operation at 100 MHz modulation frequencies, it may still be necessary to use a bank of approximately five 1 mm devices to achieve an adequate signal to noise ratio.

Table A3. LIGO I and LIGO II photo detector specifications.

Parameter	LIGO I Requirements	LIGO II Requirements
CW power	1.2 W	12 W
Unlock transient	3 J	30 J
RF signal/electrical noise	1.4×10^{10} □Hz	4×10^{10} □Hz
Quantum efficiency	80%	90 %
Spatial uniformity	1 % RMS	0.1 % RMS
Surface back-scatter	1×10^{-4}/sr	1×10^{-5}/sr

Laser

The upgrade from LIGO I to LIGO II will require increasing the laser power by a factor of almost 20. This will involve the development of diode-laser pumped, slab geometry optical gain stages that can be used either in unstable resonator injection locked power oscillators or as muti-pass power amplifiers. Nd:YAG lasers continue to be the best choice due to their operational efficiency and reliability, potential for scaling to higher powers, low intrinsic amplitude and frequency noise. There are several implementations of diode pumped Nd:YAG technology which can reach progressively higher output powers:

1. stable ring cavity with an inter-cavity étalon,
2. injection-locked stable oscillator,
3. injection-locked unstable resonator oscillator,
4. below-threshold regenerative amplifier, and
5. master oscillator power amplifier - MOPA.

Technical issues that effect the selection of a particular laser design include amplitude and frequency noise, transverse mode control, output power and the availability of good frequency and power actuation for active feedback control. Other systems issues include operational reliability, maintainability, minimizing the number of single point failure modes, and commercial support for continuing technology development. The latter is important to keep costs low by sharing the development with industry. At present, our baseline design (see Fig. A3) uses an extension of LIGO I technology: a low power low noise Master oscillator is followed by an intermediate stage which will produce an output power which will be consistent with saturated operation of two multi-pass power amplifiers.

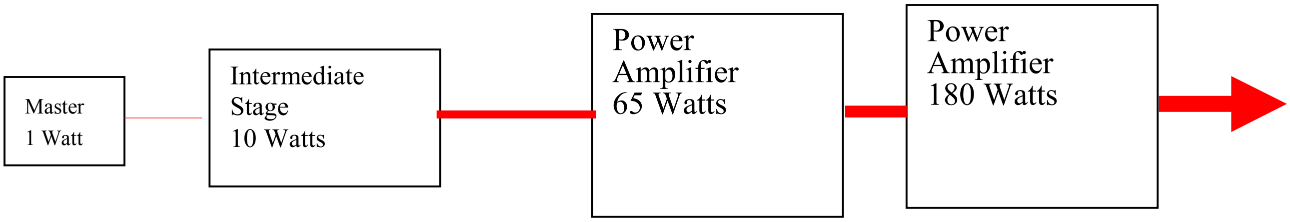

Figure A3. The basic topology of a 180 watt LIGO II laser: A low-noise master oscillator is followed by an intermediate stage which boosts the laser power up to a level where saturated amplifiers can be operated. Each amplifier is a double pass amplifier and all stages except for the master are diode pumped slab gain media.

Pre-stabilized laser

The diode laser pumped Nd:YAG slab laser will provide 180 W to the input of the LIGO II pre-stabilization system, and the output of the complete pre-stabilized laser will be 150 W. The frequency, amplitude and modal or beam wiggle noise will be stabilized to a level which will contribute no more than 0.05% to the noise budget at any frequency which is the same requirement as for LIGO I. The optical layout and control topology of the PSL system will remain largely unchanged. Detailed laser noise models are not yet complete for the signal-recycled interferometer. As an estimate of the requirements for the we have used the experience gained on the 40 m interferometer at Caltech which indicate that a factor of 10-20 times better performance is required in laser frequency, amplitude and higher order transverse mode content.

Input/Output Optics

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 photodetector will be required to handle laser powers about 20 times those in LIGO I. The basic configuration is similar to LIGO I. The higher power presents some difficulties for the triangular mode cleaner optics, but these are found also in the core optics and appear tractable. The phase modulators will be used in a configuration where they do not transmit any more power than in LIGO I. Frequency noise requirements may drive the mode cleaner to use larger (e.g., LIGO I sized) optics and more sophisticated suspensions.

Phase and Amplitude Modulators

Phase modulation is applied to the laser light to create error signals for control of the interferometer. The high power levels of LIGO II present challenges for the design and utilization of modulators, due to thermal lensing, intensity dependent refractive index, and potential for irreversible physical damage which can occur in the modulator material or coatings. In LIGO II the higher laser power passed through the phase modulators is handled in two ways. Phase modulators (and acousto-optic amplitude modulators if needed) for the laser stabilization may be placed before the pre-mode cleaner between the intermediate stage and the power amplifier of the laser. This can work because the power amplifiers, unlike a laser cavity, have little dispersion. The modulators which must be placed after the pre-mode cleaner and which are used to produce the length, pitch and yaw control signals and the main modulation sidebands will be placed in the low power arm of an auxiliary Mach-Zehnder interferometer as shown in Fig. A4.

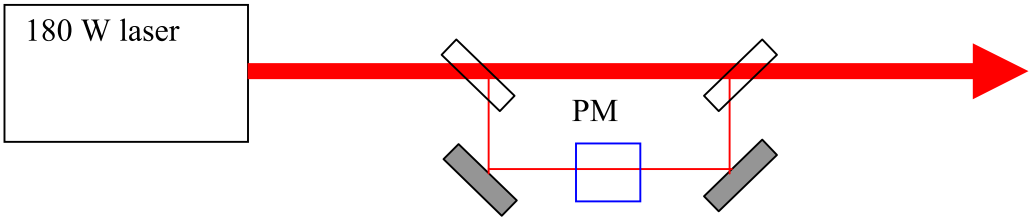

Figure A4. Phase modulator placed after the high power LIGO II laser. Using a partially reflecting mirror a small portion of the high power laser beam is passed through a phase modulator and is then interferometrically recombined with the high power beam. This avoids passing the full 180 watts through the phase modulator. Note that the length and alignment of the interferometer loop must be controlled.

Optical Isolators

The Faraday isolators both isolate the mode cleaner and laser from back-reflected laser light and deliver the back-reflected light to the length and alignment control systems. The LIGO I Faraday rotators used terbium gallium garnet (TGG) which suffered a small amount of self-induced thermal lensing even at LIGO I power levels. Absorption of laser radiation in magneto-optical materials results in a temperature gradient which induces depolarization due to both the temperature dependence of the Verdet constant and the photoelastic effect thus limiting the isolation ratio of Faraday isolators. The amount of depolarization is dominated by the photoelastic effect and is predicted to scale as the square of the laser power. For LIGO I, these effects are negligible ($<2\times10^{-4}$ power in the orthogonal polarization). At LIGO II power levels, this effect becomes 100 times greater, resulting in >1 watt of power propagating back into the laser. These effects can be reduced in two ways. The first scheme to use a second Faraday rotator and either a half waveplate or a quarter wave rotator as illustrated in Fig. A5. In these schemes the depolarization of the first faraday element is compensated by the second. These schemes have been demonstrated experimentally on a small scale and both show good agreement with theory and the promise of meeting the LIGO II goals. An alternative to be pursued if necessary involves automatic temperature control of the Faraday material using a heating beam and a wavefront sensor much like the core optics compensation.

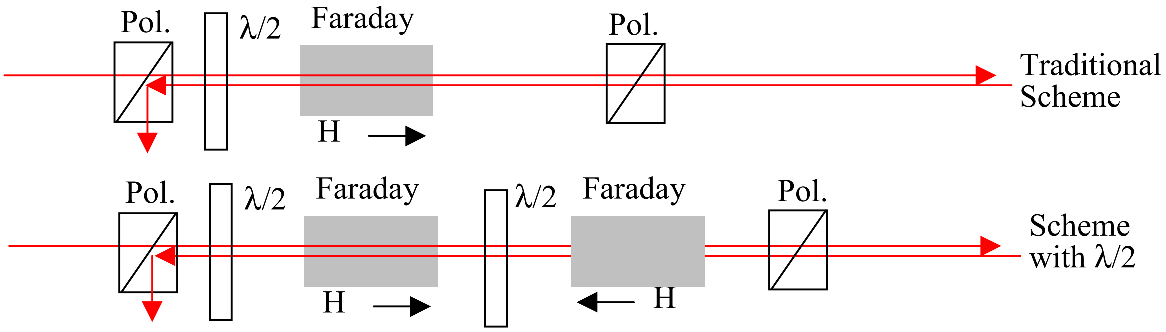

Figure A5. Two schemes for building an Optical Isolator. The top scheme is the traditional method of using a Faraday material to build an optical isolator. In the bottom scheme the second faraday rotator is used to compensate for the thermally induced variations in birefringence and Verdet Constant.

Mode Cleaners and Telescopes

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 and the mirrors are subjected to the highest power density in the system, almost 50 kW/cm^2. The roughly 20× increase in laser power planned for LIGO II will increase the power density to 1 MW/cm^2. This power, while impressive, is still below the 5 MW/cm^2 damage threshold of high-quality coatings. Thus damage (at least in the short term) is not an overriding issue. We have used a thermal model to estimate the amount of thermal lensing in a triangular mode cleaner for both LIGO I and LIGO II power levels assuming a 1550 finesse cavity (baseline for LIGO I) with fused silica mirrors. Thermal lensing distortion of the mode cleaner optics does not appear to significantly effect mode cleaner performance. However, coating absorption and absorption due to surface contamination are not included in the model and needs further investigation. This could lead to a need for higher conductivity in the mode cleaner mirrors (e.g., the use of sapphire), and/or compensation as planned for the core optics.

Suspension and Isolation Reference Design

Suspension

The suspension system is designed to preserve the low intrinsic losses (which lead to thermal noise) in the fused silica suspension fibers and sapphire test mass material, to provide actuators for length and angular alignment, and to attenuate seismic noise. The LIGO II reference design suspension is similar in design to the GEO 600 multiple pendulum suspensions, with changes to target a seismic wall of 10 Hz. The GEO 600 suspensions are in production, and some important elements of the design have been tested at ~6×10^{-19} m√Hz in the Glasgow and Garching prototypes.

There are several clear advantages to a multiple pendulum. Perhaps the most important is to provide a location to apply control forces for locating and aiming the test mass that are 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 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 mechanical 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 the suspension is the presence of additional vertical isolation.

Suspension reference design

The test masses, beamsplitter, recycling mirrors, and mode cleaner mirrors are all suspended from multiple pendulums with fused silica fibers. While each type of suspension is somewhat different in requirements and design, the test mass is the most critical and will serve as the example below.

The mirror is suspended as the lowest mass of a triple pendulum as shown in Figure A6; the three stages are in series. The reference design mirror substrate is sapphire. However, the basic suspension design is compatible with fused silica masses and a “fall-back” to this alternate may be made shortly before final design. Both materials are amenable to hydroxy-catalysis bonding of the fiber to the test mass. The mass above the mirror -- the intermediate mass -- is made of fused silica.

The mass at the top is suspended from two cantilever-mounted, approximately trapezoidal, pre-curved, blade springs (inspired by and similar to the VIRGO blade springs), and two steel wires. The blade springs are stressed up to half of the elastic limit.

The intermediate mass is suspended from 4 cantilever springs and 2 steel wire loops. Fused silica pieces form the breakoff points at the intermediate mass. These are hydroxy-catalysis bonded to the intermediate mass. The upper support stages do not have their wires vertical and this gives some control over mode frequencies and coupling factors. Tolerable noise levels at the intermediate mass are within the range of experience on prototype interferometers (10^{-17} m/√Hz) and many aspects of the technology have been tested. There are, however, no meaningful test results at less than ~ 150

Hz. At the top-mass the main concern is to avoid acoustic emission or creep (vibration due to slipping or deforming parts).

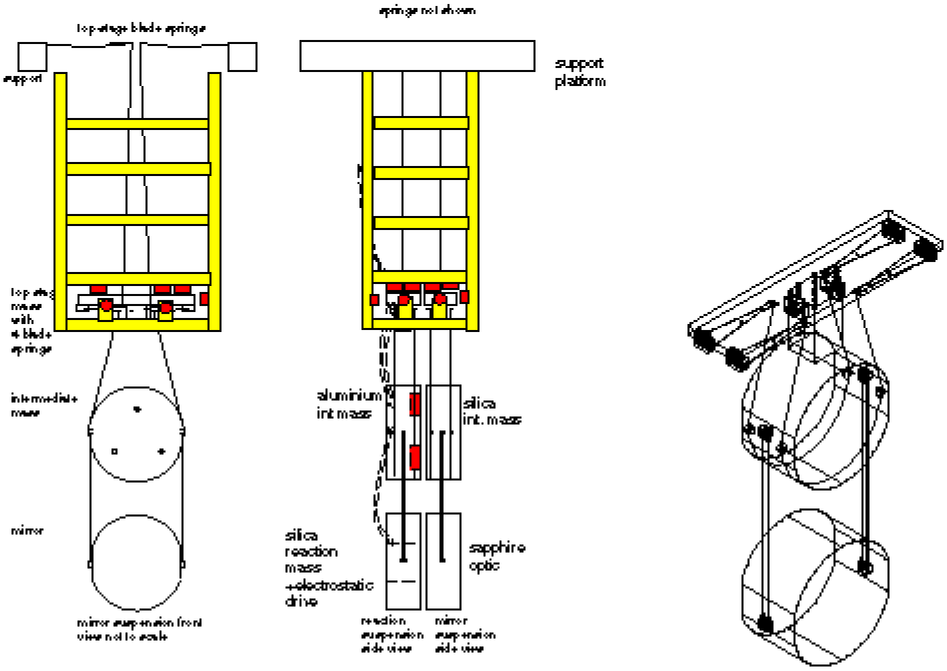

Figure A6. LIGO II suspension design.

Sensing (for damping) of modes in the triple requires modest improvements to the occultation "OSEM-like" sensors (required performance ~10^{-11} m/√Hz at 10 Hz). These sensors measure the relative position of the top masses with respect to the support structure for the triple pendulum.

Actuation is applied in a hierarchy of lower force and higher frequency as the test mass is approached. Coils and magnets are used on the top stage, with electrostatics (for locking) and photon pressure (for operation) used on the test mass itself.

Table A4. Test mass suspension parameters.

Suspension Parameter	**Value**
Test mass	30 kg, sapphire
Effective mechanical loss 'φ'	5×10^{-9}
Penultimate masses	16 kg, fused silica
Upper masses	28 kg, stainless steel
Test mass suspension fiber	Fused silica ribbon, 4×10^{-7} m^2, 1:55 aspect ratio
Upper mass suspension fibers	Steel
Effective mechanical loss "φ"	3.3×10^{-8}
Approximate suspension lengths	0.4 m test mass, 0.35 m intermediate, 0.7 m top
Vertical compliance	Trapezoidal cantilever springs
Horizontal seismic transmission	10^{-6} at 10 Hz
Test mass actuation	Electrostatic (acquisition), photon pressure (operation)
Upper stage actuation; sensing	Magnets/coils; incoherent occultation sensors

Seismic Isolation

The seismic isolation system serves to attenuate ground motion in the observation band (above 10 Hz) and also to reduce the motion in the "control band" (frequencies <10 Hz). Significantly improved seismic isolation will be required for LIGO II to realize the benefit from the reduction in thermal noise due to improvements in the suspension system. It is anticipated that the isolation system will be completely replaced, and this offers the 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.

The top-level constraints on the design of the isolation system can be summarized:

- **Seismic attenuation**: The amplitude of the seismic noise at the test mass must be equal to or less than the thermal noise of the system (10^{-19} m/√Hz at 10 Hz) for the lowest frequencies where observation is planned. We choose 10 Hz for the low-frequency cutoff because the competing noise sources (suspension thermal noise, radiation pressure, Newtonian background) all conspire to establish a presently irreducible sensitivity level at 10 Hz which is roughly a factor of 30 worse than the minimum interferometer noise spectral density, and because technical difficulties in suspension design make a lower goal unrealistic.

- **The RMS differential motion** of the test masses while the interferometer is locked must be held to a small value (less than 10^{-14} meters) to limit cross-coupling from laser noise sources. Similarly, the RMS velocity of the test mass must be small enough and the test mass control robust enough that the interferometer can acquire lock This requires reduction of the seismic noise in the frequency band from 0.1 to 10 Hz.

- **The isolation positioning system** must have a large enough control range to allow the interferometer to remain locked for extended periods; our working value is 1 week.

- **The system must interface** with the rest of the LIGO system, including LIGO vacuum equipment, the adopted suspension design, and system demands on optical layout and control.

Preliminary performance requirements are shown in Table A5.

Table A5. Isolation Performance Requirements.

Optics Payload	Optic Axis (X-direction)				Y&Z directions		Pitch, Yaw
(Chamber type)	Freq. (Hz)	Noise (m/√Hz)	*Motion* (m rms)	Velocity (m/s)	Noise (m/√Hz)	*Motion* (m rms)	*Motion* (rad rms)
ITM, ETM, BS, FM (BSC)	10	10^{-19}	10^{-14}	10^{-9}	10^{-16}	10^{-11}	10^{-6}
RM, SRM (HAM)	10	10^{-17}	10^{-13}	10^{-8}	10^{-14}	10^{-10}	10^{-6}
MC (HAM)	10	3×10^{-18}	10^{-12}	10^{-7}	3×10^{-15}	10^{-9}	10^{-6}

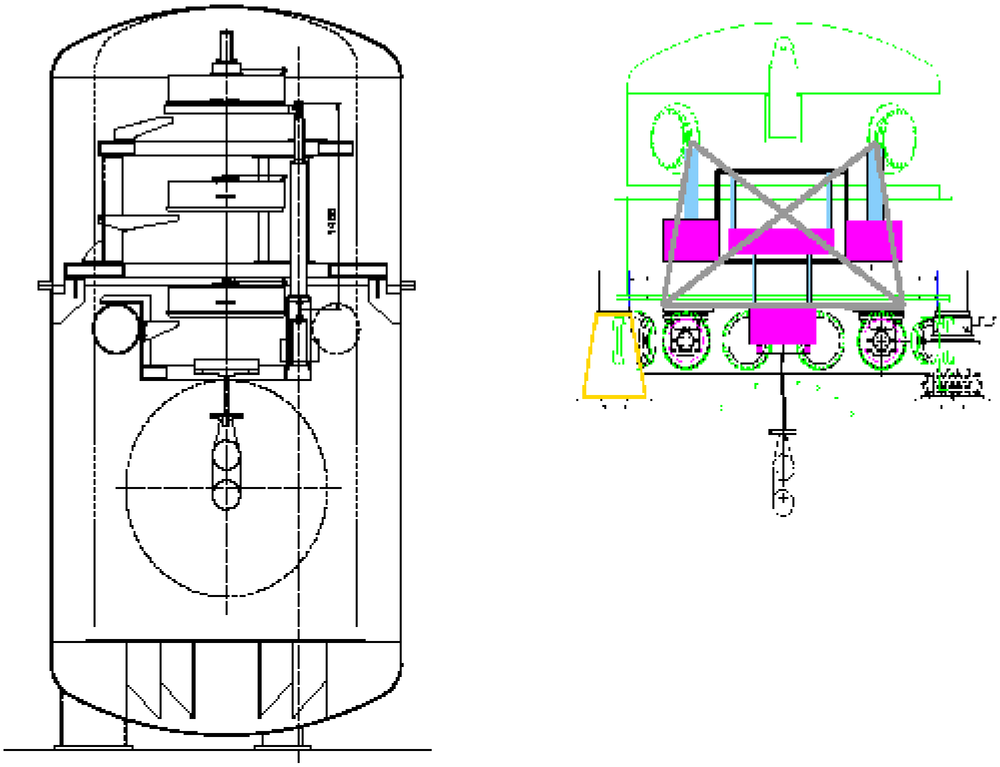

Figure A7. Two Seismic Isolation concepts for LIGO II.

Seismic Isolation Reference Design

Two approaches for attenuation of the control-band noise are under consideration. In the “soft” design, low natural frequencies are used. An inverted pendulum provides passive isolation at the microseismic (0.16 Hz) peak. This is followed by several stages of passive isolation in the form of pendulums with balanced spring mechanisms (similar to the VIRGO isolation system) to give a low vertical resonance and thus strong vertical as well as horizontal filtering. Control systems operating in the control band (less than 10 Hz) are used for damping of resonances and quasi-static positioning.

In the “stiff” design, high natural frequencies are used, and servo loops using local accelerometers and actuators bring the attenuation and control to the required level. This is conceptually similar to the isolation platform developed at JILA. Both systems use passive isolation near the suspension system to achieve the final filtering. Figure A7 shows one approach using the inverted pendulum on the left, and one using active systems is shown on the right.

Slightly less seismic attenuation is needed for the beamsplitter, power recycling mirror, signal recycling mirror, and mode cleaner mirrors. The isolation system for the HAM vacuum chambers will thus have slightly relaxed requirements compared with the BSC test mass chambers.

Mechanical Controls

To reach LIGO II performance goals for attenuation of seismic noise, thermal noise performance, and to operate the interferometer successfully, a hierarchy of servocontrols for the mechanical subsystems is needed. Due to the deleterious effects of actuators on the test mass mechanical losses (and thus thermal noise), it is highly desirable to reallocate control authority away from the test mass. Seismic excitation in the 'control band' (10 Hz and lower) dominates the RMS excursion of the ground, and thus defines the requirement on actuator authority. Proper design will also improve interferometer availability by improving the robustness of the fringe locking servo and the rapidity of lock acquisition.

The principal control functions addressing mechanical motion of the test masses are:

- re-allocation of control authority away from the test mass,
- distribution of the main interferometer feedback signals in an optimized way to the suspended masses and external actuators,
- potentially, in-band 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 (0.16 Hz) peak.

The controls will use multiple-input multiple-output servosystems, with digital processing of the signals. This allows flexible designs, which can be optimized manually (or ultimately in an automated fashion) during the development and the operational implementation. The controls design will be made in parallel with the mechanical development to ensure that mechanical modes are observable and controllable by design.