Strawman LIGO II Design: A Quantum Limited Interferometer for LIGO

D. Shoemaker, K. Strain, E. Gustafson 9 July 99

Introduction
This is a working draft, and by definition not finished or final.

The objective of this strawman design is to establish a paradigm for discussing possible improvements to LIGO starting in 2004. The strawman describes the endpoint of LIGO II upgrades; some aspects of the design could be implemented relatively early in the time window (2004-2008), and others are not likely to be available for technical reasons until late (~2006).

A description with few options is first given, not because there is unanimity on all design questions among those participating in design discussions, but to simplify the description. The document profits from the work of many, but the particular viewpoint is of the authors and any peculiar attitude, errors and/or narrow-mindedness are their fault alone.

Summary of design
The basic optical configuration is a power-recycled and signal-recycled Michelson interferometer with Fabry-Perot ‘transducers’ in the arms. This requires the addition of a signal recycling mirror to the suspended optics at the output ‘dark’ port, and changes in the RF modulation and control systems. 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 by roughly a factor 15 (optimized for the desired interferometer response, given the quantum limit); the input optics, and modulators and isolators must be modified to accommodate the increase. Heating rings are added near the test mass optics to correct for thermal lensing.

The testmass optics are made of c-axis sapphire, roughly 28 cm diameter, 30 kg mass. 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 I (somewhat lower scatter and/or end-mass transmission desirable).

The isolation system is built on the LIGO I piers and support tubes. RMS motions (frequencies less than 10 Hz) are reduced by a combination of active and passive techniques, principally in-vacuum, but possibly with actuators mounted in place of the scissors tables and present air bearings. Two passive pendulum stages are used to filter in the GW band (10 Hz and greater).

The suspension has three pendulum stages, and resembles closely the GEO suspension. The test mass is suspended by fused silica ribbons attached with hydroxy-catalysis bonds. Electrostatic forces are used on the test mass for locking the interferometer; photon pressure is used in the operational mode. Local sensors (electrostatic and occultation) and magnets/coils are used on the upper two stages for damping, orientation, and control.
**Requirements**

The LIGO II interferometer is quantum noise limited at all usable frequencies for the normal operating conditions.

Radiation pressure dominates at low frequencies (10 Hz to 100 Hz), with the 10 Hz seismic ‘brick wall’ intercepting the radiation pressure at a level about a factor of 10 above the best strain sensitivity. Shot noise dominates at high frequencies (>100 Hz). Resonant Sideband Extraction (RSE) allows the shot noise to be adjusted to best match the limit due to internal thermal noise or to increase the sensitivity at a specific frequency (as limited by the other underlying noise sources and the optical limits). The internal thermal noise is approached at ~100 Hz, the most sensitive region.

The technical limits that determine the overall sensitivity are

1. Optical substrate and coating absorption losses, which limit the power circulating in the interferometer to ~5 kW in the inner Michelson and ~650 kW in the arm cavities
2. The test mass, limited to ~30 kg by fabrication limits for optical materials; this with the circulating power and optical scheme determine the radiation pressure.

Secondary limits which lie under the above are

1. Pendulum thermal noise, limited by fused silica ribbon suspension fibers to ~1/2 the radiation pressure noise
2. Newtonian background, limited by the observatory characteristics to ~1/2 the radiation pressure noise (at 10 Hz, smaller at higher frequencies)
3. Test mass internal mode thermal noise, limited to ~1/2 the shot noise at 100 Hz by mechanical losses in sapphire.

Because of the tunability of the readout scheme, no single response or sensitivity curve describes the interferometer; however, a sample optimized for inspiral detection is shown in Figure1, generated using [http://fiji.nirvana.phys.psu.edu/~swg/CBI.html](http://fiji.nirvana.phys.psu.edu/~swg/CBI.html).
Figure 1: sample LIGO II sensitivity curve. The list of parameters used is shown in the Table below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>~170 W</td>
<td>IO efficiency 0.75</td>
</tr>
<tr>
<td>Input power to recycling mirror</td>
<td>125 W</td>
<td>Optimized for ns-ns inspiral</td>
</tr>
<tr>
<td>Mirror loss (transmission+scatter)</td>
<td>20 ppm</td>
<td>Similar to LIGO I</td>
</tr>
<tr>
<td>Effective power recycling</td>
<td>90</td>
<td>~ Double that of LIGO I</td>
</tr>
<tr>
<td>Substrate absorption</td>
<td>20 ppm/cm</td>
<td>Equiv. to 0.5 ppm/cm in silica</td>
</tr>
<tr>
<td>Thermal lensing correction</td>
<td>Factor 10</td>
<td>Using circular heating elements</td>
</tr>
<tr>
<td>Suspension fiber</td>
<td>Fused silica ribbon</td>
<td></td>
</tr>
<tr>
<td>Test mass</td>
<td>Sapphire, 30 kg</td>
<td>28 cm dia, 12 cm thick</td>
</tr>
<tr>
<td>Signal recycling mirror transmission and phase</td>
<td>T=0.36; phi=1.0 rad</td>
<td>Optimized for ns-ns inspiral</td>
</tr>
</tbody>
</table>
Description by subsystem

Configuration and controls

The configuration of the optical system of the interferometer employs signal recycling. This is operated in the mode known as resonant sideband extraction.

Requirements: The configuration and associated control systems shall deliver shot-noise and radiation-pressure limited phase sensing which best exploit the thermal noise and test mass available. Degradation due to imperfect lengths/alignment shall be less than 10%.

Signal recycling: The signal recycling mirror (SRM) is placed between the normal output port of the Power Recycled Fabry-Perot Michelson (PRFPM) interferometer and the photodiodes that normally detect the output light. Just as the ‘PR cavity’ can be said to exist, we can now validly use the term ‘SR cavity’ to describe the resonant system formed by the PRFPM and the SRM. When the interferometer is at the nominal dark-fringe operating condition with the PR cavity resonant, the SRM works with the two ITMs 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 ITM and SRM transmittances allows the bandwidth of the interferometer to be determined. The position of the SRM, 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 (DR), while when the bandwidth of the (high finesse FP arm cavities) is increased it is called resonant sideband extraction.

The curvature of the SRM is selected to ensure that the cavity formed by this mirror and the PRFPM 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.

Additional control for the signal recycling mirror: The position of the signal recycling mirror determines the tuning frequency of the interferometer (frequency of peak optical system response). Suitable control signals can be extracted by appropriate combinations of Schnupp and Pound modulation schemes TBD with pick-off ports TBD. Feedback to control the position of this mirror would be done analogously to feedback to control ITM and ETM positions, with generally slightly less stringent requirements on noise etc. The types of modulation and pick-off ports are similar to those provided for a basic PRFPM. Additional signals required to control the SRM are relatively simple to produce; changes to the read-out method for the main dark-port signal are more significant. Programs used in the analysis of the interferometer and further information can be found at http://www.phys.ufl.edu/LIGO/LIGO/STAIC.html.

Length and Alignment Sensing and Control: The implementation of RSE, and generally reduced system losses will require a completely re-designed sensing (read-out) system for length (and also probably for alignment). There will have to be a complete re-analysis of the noise breakdown. Prototypes are presently testing several schemes.

Length and alignment control (feedback) will be more complex: 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.
**Pre-stabilized Laser**

A diode laser pumped Nd:YAG slab laser will provide ~170 watts to the input of the LIGO II pre-stabilization system. The pre-stabilized laser will provide ~125 watts of 1064 nm radiation at the power recycling mirror. 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 (as for LIGO I). The optical layout and control topology of the PSL system will remain largely unchanged.

**Laser frequency and intensity noise:** Models are not yet complete for the signal-recycled interferometer. An estimate of the requirements for the laser source have been made using the LIGO I interferometer models, and with the assumption that no other changes (trades) are made in the requirements for the interferometer.

**Table 1:** Frequency and amplitude noise requirements, for a power-recycled (not signal-recycled) interferometer, to realize the shot-noise limited detection of 125 W (as planned for LIGO II).

<table>
<thead>
<tr>
<th>Laser Noise</th>
<th>Frequency Noise [Hz/rHz]</th>
<th>Intensity Noise [1/rHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 Hz</td>
<td>150 Hz</td>
</tr>
<tr>
<td>LIGO I</td>
<td>1x10^-7</td>
<td></td>
</tr>
<tr>
<td>LIGO II</td>
<td>1x10^-8</td>
<td>5x10^-9</td>
</tr>
<tr>
<td></td>
<td>8x10^-7</td>
<td>2x10^-7</td>
</tr>
</tbody>
</table>

**Input Optics**

The basic configuration is similar to LIGO I, with a triangular mode cleaner, matching telescope, and phase modulation. The higher power presents some difficulties for the mode cleaner optics, but these are common to the core optics and appear tractable. The phase modulators will either have to be substantially improved in power handling or used in a configuration where they transmit less power. Frequency noise requirements may drive the mode cleaner to use larger (e.g., LIGO I sized) optics and more sophisticated suspensions.

**Core Optics**

Test mass materials must exhibit low internal thermal noise which limits interferometer sensitivity at the noise minimum near 100 Hz, and high thermal conductivity in combination with low absorption to keep thermal lensing acceptably small. Candidates are Sapphire, YAG and GGG, all transparent materials with high thermal conductivity. Sapphire is known to have a lower mechanical loss factor than fused silica and YAG is a hard cubic crystalline material that is easily polished and figured. It has yet to be demonstrated that any of these materials can be grown in large sizes and polished to LIGO’s specifications.

For the purposes of this document the four test masses are assumed to be made of sapphire. The test masses must be C-axis to minimize birefringence. The 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 is made of the best presently available low absorption fused silica, and the power recycling mirror, and signal recycling mirror of LIGO I-class fused silica. The fused silica optics are LIGO I sized. The mirror curvatures are similar to those of LIGO I, the transmission of the recycling mirror is about 3 times smaller than in LIGO I, and the input test mass transmissions are 3%.
Surface Figure and Microroughness: Table 2 shows the LIGO I and II figure and microroughness requirements, along with the best obtained to date in silica. The polishing required for LIGO II core optics for long spatial wavelengths is about 2.5 times better than the best obtained to date in silica. With an increase of a factor of 27 in input laser power and tripling of the power recycling factor to 90 with the same input mirror reflectivity as LIGO I, the LIGO II absorption loss in the substrate and coating can be estimated and is done so in table 2. The sapphire substrate is required to absorb no more than 20 ppm/cm, which is a factor of 2 better than the best small samples available today.

Table 2: Sapphire Core Optics Polish and Figure Requirements

<table>
<thead>
<tr>
<th>Sapphire Core Optics</th>
<th>LIGO I Requirements</th>
<th>LIGO II Requirements</th>
<th>Best to Date Small Silica Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Figure</td>
<td>1nm RMS</td>
<td>0.5 nm RMS</td>
<td>0.5 nm RMS</td>
</tr>
<tr>
<td>Micro-Roughness</td>
<td>0.5 nm RMS</td>
<td>0.2 nm RMS</td>
<td>0.2 nm RMS</td>
</tr>
</tbody>
</table>

To obtain a power recycling factor of 90 the recycling cavity losses must be below 1% (possible with LIGO I coating/polishing technologies). Overcoupled arm cavities require a total arm loss<1%, so optic loss ~ 1%/130 ~100 ppm. This is met with present optics.

Absorption in Substrates and Coatings: 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 correction using heating rings. The beamsplitter will also require compensation for thermal effects. The heating rings add a complementary heat source in an annulus at the mirror face, which, along with the laser heating, give a first order optically flat surface (at a slightly higher overall temperature). The coatings are assumed to be the best presently observed coatings on silica.

Table 3: Sapphire test masses and coating absorption requirements

<table>
<thead>
<tr>
<th>Sapphire test masses</th>
<th>LIGO I, Silica</th>
<th>LIGO II, Sapphire</th>
<th>Best to Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Absorption</td>
<td>5 ppm/cm</td>
<td>20 ppm/cm</td>
<td>40 ppm/cm</td>
</tr>
<tr>
<td>Coating Absorption</td>
<td>0.5 ppm</td>
<td>0.2 ppm</td>
<td>0.5 ppm</td>
</tr>
</tbody>
</table>
Suspension
The LIGO II suspension is similar in design to the GEO 600 suspensions, with changes to target a seismic wall of 10 Hz. The GEO 600 suspensions are in production, and many elements of the design have been tested at $\sim 1 \times 10^{-19}$ m/rHz in the Glasgow and Garching prototypes. See Figure 2 below for a schematic drawing.

Requirements: The suspension system design shall not increase the losses leading to thermal noise in the fused silica suspension fibers ($\phi = 3.3 \times 10^{-8}$) or sapphire test mass material ($Q = 5 \times 10^{-9}$) by more than 20% each. This places constraints on the attachments, actuators, and overall configuration. Control points for length and angles will be provided.

Physical description: The mirror is suspended as the lowest mass of a triple pendulum; the three stages are in series. The mirror substrate is Sapphire. This material is amenable to hydroxy-catalysis bonding. The mass above the mirror -- the intermediate mass -- is made of fused silica. These two masses are connected by vertical fused-silica fibers. The four support fibers are welded on to fused-silica prisms that are hydroxy-catalysis bonded to flat areas polished on the sides of the mass. The remaining structural parts (further from the test mass) are fabricated from metals. The suspension is designed to cause no appreciable increase in the test mass material thermal noise. To achieve this the mirror is unmodified apart from the carefully designed attachments noted above.

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 to about 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/rHz) and many aspects of the technology have been tested. There are, however, no meaningful test results at less than $\sim 150$ Hz. At the top-mass the main concern is to avoid acoustic emission or creep (vibration due to slipping or deforming parts).

The lower stage wire resonances are pushed as high as the silica fibers allow with a first set of modes at $\sim 400$ Hz. The performance of the other stages depends much more on the blades than on the wires.

The first unwanted mode of the upper set of blades (at about 120 Hz) requires passive damping (using a resonant damper). A vacuum compatible damper is currently under design/investigation. The lower blades have their first internal resonance at 220 Hz which is not problematic.

Sensing (for damping) of modes in the intermediate (penultimate) mass requires a capacitive bridge, interferometer, or improvements to the occultation ‘OSEM-like’ sensors (required performance $\sim 10^{-12}$ m/rHz at 10 Hz).

Actuation is applied to all masses in a hierarchy of lower force and higher frequency as the test mass is approached. Coils and magnets are used on upper stages, with electrostatics (for locking) and photon pressure (for operation) used on the test mass itself. Suspension fiber monitors and damping of the fibers after locking can be incorporated but need significant development.
Figure 2: LIGO II suspension

Seismic Isolation

The seismic isolation system serves to attenuate in the observation band and also to reduce the motion in the ‘control band’ (frequencies less than 10 Hz) quite significantly.

Requirements and assumed design constraints:

1) 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/rHz at 10 Hz) for frequencies above 10 Hz and less than 1/10 the thermal noise by 12 Hz.

2) The RMS motion of the test mass while the interferometer is locked must be less than 10^{-14} meters (a factor of ten smaller than LIGO I).

3) The RMS velocity of the test mass must be small enough and the test mass control robust enough that the interferometer can acquire lock (TBD, but presently ~1/4 of LIGO I).

4) The mirror control system has a large enough control range to allow the interferometer to remain locked for 3 months (a seasonal change).

5) The system must fit into the existing vacuum chambers.

Two approaches for attenuation of the control-band noise are under consideration. In one, an inverted pendulum provides passive isolation at the microseismic (0.16 Hz) peak. In the other, a combination of an external ‘slow’ actuator and an internal 5 Hz spring stage are used for actuation. In both approaches, servo loops using local accelerometers and ‘global’ interferometer signals bring the attenuation and control to the required level. Both approaches also deliver significant attenuation in the GW band (f>10 Hz).

Two stages of passive isolation in the vacuum follow. These stages are pendulums (as opposed to compressed springs) and may use simple cantilevers, coil springs, or may use spring-countersprings to deliver low vertical resonant frequencies. They provide a platform to which the suspensions (test mass, and in some cases folding mirror) will be attached. A sketch of one approach using the inverted pendulum is shown on the left, and one using active systems is shown on the right.
Somewhat less seismic attenuation is needed for the beamsplitter, power recycling mirror, signal recycling mirror, and mode cleaner mirrors. Requirements have not yet been developed, but there may be a requirement for an additional type of seismic isolation (or a significant modification of the LIGO I stacks) for the HAM chambers.

More discussion of the active systems can be found in on the Suspension/Isolation Working group web pages, http://fiji.nirvana.phys.psu.edu/~swg.
Status, Options, Challenges by subsystem

Staging of improvements
A coherent approach to staging improvements to LIGO, as dictated by the availability of technologies, consists of the following.

- LIGO IIa, ~2004: incorporation of improved isolation, GEO-like suspension, incrementally higher power laser (50-100 W), and 30 kg fused silica test masses. This delivers the low-frequency improvements and a quantum limited sensing system. This would be a major upgrade with a nearly complete reconstruction of the mechanical part of the detector.

- LIGO IIb, ~2006: incorporation of sapphire test masses, RSE interferometer sensing system, and possibly further incremental increases in the laser power. This reduces the broad-band noise floor and the RSE readout allows exploitation of that improvement. This could be a minor upgrade, with a swap of the suspension and the addition of one suspended mirror.

The obvious problem with this is the time lost to observation for installation of these upgrades. A sense of this cost in time comes from an estimate of the time to (simply) remove and re-install the LIGO I isolation system of ~18 man-years which might be possible in ~9 months under optimistic assumptions. Installation and shakedown of the optics etc. follows, of course. For reference, LIGO I is planned to require very roughly 2 years for installation and shakedown. Alternatives are to wait till ~2005 to allow one or more of the later technologies to ripen for a single upgrade (and thus to observe with LIGO I for three, not two, years); or to make a second upgrade later and extend the LIGO II epoch to 2009 or 2010.

Configuration
Enough is known about the modeling of resonant sideband extraction interferometers to allow the selection of configuration to take place on a short timescale. The required inputs are

- a decision on science goals (prioritisation)
- reliable estimates (or bounds) for substrate and coating loss (scattering, absorption), laser power and ability to provide adaptive correction of the thermal lens

Length and Alignment Control
Experimental demonstrations on a prototype dual recycled Michelson with suspended optics (but no arm cavities) have confirmed the practicality of operating signal recycling interferometers. These tests have also allowed a number of design tools to be qualified. The process from our present state of knowledge to a complete engineering design is the following:

1. Selection of an outline control solution based on site constraints, complexity, etc.
2. Analysis of noise performance
3. Analysis of lock acquisition
4. Construction of an experimental demonstrator to confirm that the technology is well understood
and to obtain deeper insight into its design and operation.

5. Final selection of the sensing scheme

6. Engineering prototype demonstrations of the sensing and control method

It is intended that steps 1 and 2 be carried out before the end of 2000, steps 3 through 5 by late 2002 and steps 5 and 6 by late 2004. These estimates are based on the expected availability of personnel at the key locations over the next 4 years. Acceleration would be possible given increased human resources.

Pre-stabilized Laser

A 170 Watt diode laser pumped Nd:YAG is largely an engineering task and there are several different laser topologies which could meet our requirements. For example, a 10 watt LIGO laser as the master oscillator amplified through 4 of currently existing slab amplifiers should provide approximately 180 Watts. Calculations to determine the frequency, amplitude and modal or beam wiggle noise are required for a signal and power recycled interferometer but are not expected to be much different from the numbers in Table 1 above. The pre-mode cleaners will be operated at a power which is at least 27 times above their current circulating power and will require improved coatings and the lower absorbing glass. These improved coatings are within the state of the art of the present best 1064 nm coatings unless additional temporal filtering is required in which case two pre-mode cleaners may be required. Moreover reduced diode laser pump fluctuations in the NPRO master oscillator could reduce the low frequency and amplitude noise by an order of magnitude

Input Optics

The configuration of the mode cleaners and telescopes will be largely those of LIGO I. The higher laser power will for a suspended mode cleaner finesse comparable to LIGO I require a mirror coating absorption which is roughly half that of the best coating available today to achieve the same level of wave front fidelity, or a heat-ring compensation (see below).

While the phase modulators will need to be used at higher optical power than in LIGO I they will not necessarily operate with the full laser power, e.g., the phase modulators can be used in one arm of a Mach-Zehnder while the majority of the laser power travels through the other arm or for those modulators which proceed the pre-mode cleaner they can be placed before the optical power amplifier. If current lithium niobate phase modulators can be restricted to transmitting beams of no more than 10 watts of power and less than 20 kW/cm2 of intensity they should be satisfactory for LIGO II.

The optical isolators, however, will need to be placed in the full power of the beam and new materials or methods must be developed. Faraday rotators using terbium gallium garnet (TGG) suffer self-induced thermal lensing at LIGO I power levels that reduce power coupling into the interferometer by a few percent (due to the addition of higher cylindrical modes caused by the Gaussian nature of the thermal lensing) and at LIGO II power levels thermal focussing will become severe and will seriously degrade coupling efficiency. We estimate that for 100 W powers, only 40% of the light is remaining in the fundamental Gaussian mode.

Absorption of laser radiation in magneto-optical materials results in a temperature gradient that induces depolarization due to both the temperature dependence of the Verdet constant and the photoelastic effect. Thus, it can limit 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 x 10^{-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. This level of isolation is insufficient for LIGO operation.

**Core Optics**

There is uncertainty if transmissive crystalline optics will be available even in 2006. Non-transmissive crystalline optics (for the ETMs) may have more lax requirements, but still require development. Replacing only the ETMs would make an incremental improvement in the internal thermal noise limit of the interferometer (order of, but less than, root(2) improvement; reduction factor ~2 in seeing for ns-ns). An alternative for the near term is fused silica, using larger masses to achieve ~30 kg (required to hold the radiation pressure noise down). Masses of this size are being fabricated for use in VIRGO but would require coating with absorption below 0.1 ppm/cm.

The material selected for the upgrade to crystalline core optics must be compatible with a low loss bond to the suspension system; Sapphire meets this requirement, with YAG and GGG to be tested. An additional concern is mechanical losses due to the coating, which are under investigation.

**Active core optic compensation:** LIGO I was designed for a laser input power of only 6 watts, nevertheless, bulk absorption in the input mirrors and beamsplitter substrates are predicted to induce thermal distortions which must be compensated by incorporating an additional curvature into the recycling mirror. In LIGO II, which will have 60 times higher circulating power at the input mirrors. One approach to solving this problem is to improve the core optics materials. However by depositing heat on the face of the optic, it is possible to introduce a thermal component which cancels virtually any form of distortion (indeed, even initial figure distortions unrelated to laser beam loading may be compensated). Initial tests of this method by Muller (Ph.D. Thesis, Hanover, 1995) scanned a Nd:YAG laser to thermally correct optics in a visible-light interferometer and significantly improving the fringe contrast. Tests are underway for the use of simple ring heaters to cancel the principal effect of the cylindrically symmetric Gaussian deformation. We are planning on a factor of 10 reduction in the wavefront distortion.

**The status of crystalline materials potentially suitable for LIGO II:**

**Sapphire:** A-axis-oriented right circular cylinders of undoped optical quality (‘Hemex’-grade) sapphire are currently grown by Crystal Systems, Inc. (CSI) using the heat-exchanger method for use as windows in aerospace applications. The dimensions of these boules are roughly 33 cm dia. x ~15 cm high, and 40 cm dia x ~15 cm high, with the optic axes lying perpendicular to the boule axis. We are not aware of another supplier of optical quality sapphire with dimensions close to the LIGO II specifications. CSI's sapphire crystals exhibit lattice distortions which vary with position in the boule due to thermal gradients present during growth, thermal expansion anisotropy, etc.

C-axis-oriented boules are not grown by CSI because their optical and structural quality is much lower than that of a-axis boules: c-axis-oriented cylinders must instead be cored from a-axis-oriented boules transverse to the growth direction. Because CSI's current growth technology produces boules only in the range of ~15 cm high, modifications to their growth process will be needed to produce a-axis-oriented boules that are tall enough to core out a 30 cm dia. cylinder for a LIGO II optic.

Analyses of a number of undoped CSI sapphire crystals have consistently shown optical absorption in the range of 40-50 ppm/cm at 1064 nm. Known impurities in their starting material include Ti^{3+} in the 1-2 ppm range, which is readily detectable in the grown crystals by its fluorescence in the
visible. It has not yet been determined if the residual absorption at 1064 nm is related to this or another impurity, and studies are underway and will need to continue.

Sapphire is a much harder material than fused silica, and may present significant difficulties for polishing until specialized techniques are developed. While the end-test masses are not used in transmission, C-axis orientation may still be needed to avoid differential thermal expansion.

**YAG:** Measurements of acoustic attenuation at microwave (GHz) frequencies have shown YAG to have levels of mechanical loss comparable to those of sapphire. Compared to sapphire which is optically birefringent, YAG is optically isotropic which is desirable for transmissive optics. So far, optical losses below the 100 ppm/cm range at 1064 nm in nominally undoped YAG have not been obtained and it is uncertain whether or not this is an intrinsic property of the material.

Undoped YAG is grown in sizes up to 12.5 - 15 cm dia by the Czochralski method at Bicron (formerly Union Carbide - Crystal Products) and elsewhere. Like sapphire, crystals typically exhibit varying levels of lattice distortion as well as a related "core defect" because of the high thermal gradients intrinsic to the Czochralski process. A few proof-of-principle undoped and "core-free" YAG crystals of similar dimension have been grown by the heat-exchanger method at Crystal Systems, but the process is not used for the production of YAG. It is scalable, however, and thus is a possible candidate to grow YAG crystals of LIGO dimension.

**Silicon:** Single crystals of Czochralski-grown, dislocation-free (EPD < 5 cm\(^{-2}\)) silicon are readily available on the commercial market in sizes to 40 cm dia. Czochralski-grown silicon typically has oxygen present at 3×10\(^{18}\) cm\(^{-3}\) and carbon present at 5×10\(^{16}\) cm\(^{-3}\). D. F. McGuigan et al. J. Low Temp. Physics 30, 621 (1978) report mechanical Q's of 4×10\(^{7}\) in similar material with unpolished surfaces. Studies must be carried out to elucidate the effects of surface polish on Czochralski-grown silicon, and to determine the mechanical Q's of float-zone-grown silicon which has significantly lower oxygen and carbon concentrations and might be expected to be even higher. The thermal noise performance of Silicon is poorer than the other materials for a given Q due to its lower density.

**Suspension**

The fact that the suspension resembles the GEO design gives a near-term high-sensitivity test of performance as well as tests of production and reliability of many aspects of the design.

The principal difference is in the lower operating frequency (10 Hz) and greater mass (30 kg). The pendulum length must be increased to lower the vertical ‘bobbing’ resonance. Sensors for local control and low-force actuators, all with tested performance at ~10 Hz and at ~10\(^{-20}\) m/rHz are needed. There is a lack of experience with suspended masses as great as 30 kg (GEO uses ~6 kg) with fused silica suspension fibers. No fundamental problem is seen here, but considerable experience is needed. Ribbons (rectangular cross-section fibers) have been made and tests of losses made. However, there is little experience with the practical aspects of suspending masses from ribbons.

**Isolation**

There are several competing designs for the isolation system. The stated philosophical difference between the approaches is nominally active versus passive: Either natural low resonant frequency oscillators in series are employed, with minimal control systems to maintain the operating position, or relatively high natural frequency oscillators are used, with low-noise sensors and high-gain servo
systems employed to attenuate seismic noise. In either case, passive elements (pendulums with or without spring-counterspring mechanisms to lower the vertical resonant frequency) are needed close to the test mass.

In fact, the designs have more in common than not, and perhaps the key difference is whether an inverted or non-inverted pendulum is used as one of the outer-most elements. Both require some level of servo control, some level of passive attenuation, and a significant prototype test. The inverted pendulum is being developed by VIRGO, and will be tested there (with some differences from the designs proposed for LIGO II); the active systems have had principles tested at JILA and elsewhere. Any design giving a ‘brick wall’ at roughly 10 Hz, our design requirement for LIGO II, will require significant design and testing before it can be ready to install. A 2004 installation date is very challenging.

Two truly different options should be mentioned.

- A minimal change in the isolation system could be made, in which the present down-tube, springs, and masses remain in place; they are lifted by ~30 cm to accommodate the GEO suspension system; and an external pre-isolator (air pillows or PZTs) is added to reduce the RMS motion. This is attractive because of the large change in ‘seeing’ (roughly an improvement of a factor of 6 in distance for ns-ns over LIGO I, to be compared with 20 for the full LIGO II upgrade) for a small change in technology, and might (this requires scrutiny) be an upgrade which impacts observing time minimally, allowing a later major upgrade.

- A maximal change in the isolation system could be made, where a VIRGO-like multiple pendulum system is used with a tall inverted pendulum for RMS control. This does not require high-gain servo systems, and removes one set of development tasks (wide-bandwidth control and high-sensitivity accelerometers in the vacuum system) for a different set: analysis of the complicated mechanics, modifications of the vacuum system, and development of a prototype testbed capable of accommodating this structure. This system should attenuate seismic noise quite effectively, although the large number of mechanical modes and general mechanical complexity gives many opportunities for the unexpected.