LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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The LIGO Project: Progress & Plans

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THE LIGO PROJECT: PROGRESS & PLANS

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The LIGO project is currently under construction, building three interferometers at two remote sites in the U.S. Construction of the two facilities is at present approximately 50% complete, and the development of the detectors is well underway. The initial LIGO interferometers are power recycled Michelson interferometers, with Fabry-Perot cavities in the arms, and are illuminated with 6 W of 1064 nm light. This article reports on the status and reviews highlights of the design of the main detector subsystems – the laser system, the large optics, the sensing and control systems, the seismic isolation and suspensions, the physics environment monitor, and the data acquisition system. The rough schedule for the remaining design and installation work is discussed, as well as the plans for the first data run and improvements to the initial designs.

1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is currently under development by the California Institute of Technology and the Massachusetts Institute of Technology [1], with funding from the National Science Foundation. The scientific aim of LIGO is the detection and study of gravitational waves. Initially, LIGO will consist of three interferometers operating in coincidence at two sites (Figure 1). The sites at Hanford, Washington and at Livingston Parish, Louisiana will each contain one 4 kilometer arm-length interferometer, and the Hanford site will also house a second, 2 kilometer arm-length interferometer. In addition to the timing coincidence afforded by this scheme, the 2:1 length ratio will aid in the rejection of false signals by demanding the same ratio of inferred strain amplitude for candidate signal events. The orientation of the arms at the two sites is such that one arm of each interferometer makes the same angle relative to the great circle that passes through the vertices of the two sites; the second arm at each site (perpendicular to the first) lies very close to the local horizontal plane. This relative orientation provides near maximum coincidence sensitivity to a particular gravity wave polarization.

Accurate absolute timing will be achieved by synchronizing to the Global Positioning System (GPS) at the two sites – all data will be time-stamped with an absolute accuracy better than 10 μsec and a resolution better than 1 μsec. This allows correlation of data not only between the LIGO sites, but also between LIGO data and other detectors, such as other interferometer detectors, resonant bar detectors, high energy particle detectors and electro-magnetic astronomical observations.

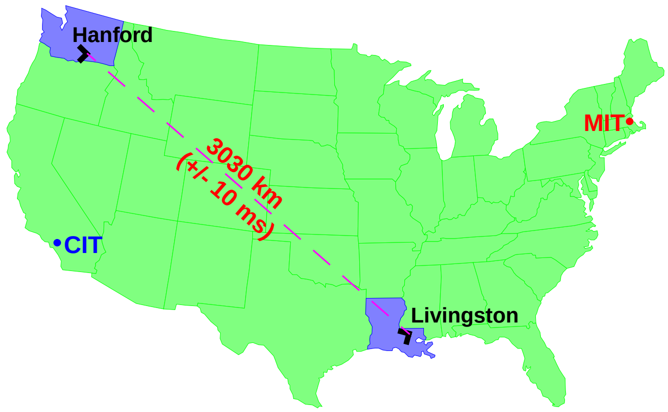


Figure 1: LIGO Sites. Two widely separated sites are located in Hanford, Washington and Livingston Parish, Louisiana. The distance between the sites is 3030 km, corresponding to a maximum difference in the time-of-arrival of ±10 msec.

2 Status of Facilities Construction

As of this writing in the summer of 1997, the construction of the facilities at the two sites – including the civil construction, the beam tubes, and the vacuum equipment – is approximately 50% complete. At Hanford, the full 8 km of beam tube and tube cover have been installed, and the vacuum equipment is beginning to be installed at the ends of the tubes. The buildings which house the installation are nearly complete. Construction activities at the Livingston Parish site are scheduled to be 6-9 months behind Hanford. Currently in LA, the buildings are in construction, the concrete support slabs for the beam tubes are complete, and the beam tube contractor is beginning to produce tube sections at a nearby factory for imminent installation.

The beam tubes are constructed by Chicago Bridge & Iron from stainless steel, specially annealed to reduce the hydrogen content. The steel is rolled and welded into spiral tube sections approximately 20 m long and 1.22 m diameter; these sections are trucked to the site and butt-welded together to form four 2 km beam tube modules. The tubes are covered with an arched concrete enclosure to protect them from the environment. The outgassing and leak rates of the tubes must be low enough to afford an ultimate pressure less than 10^{-9} torr in advanced LIGO (to reduce the phase noise due to pressure fluctuations in the residual gas), though for initial LIGO a pressure of less than 10^{-6} torr is sufficient. At this time, pump-downs of the first two 2 km modules at Hanford indicate that they meet these requirements. In addition, the mechanical alignment of the first 4 km arm at Hanford has been surveyed, indicating that the tube is straight to within ±1 cm over its length.

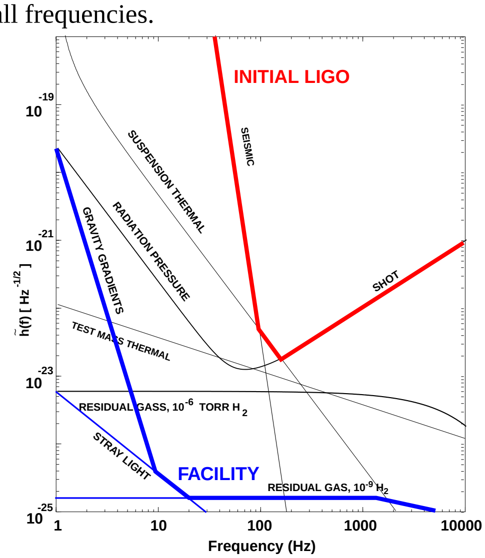
Approximately 300 internal baffles are installed in each arm to attenuate scattered light that could produce phase noise. Each baffle is a conical section, constructed of stainless steel; the steel is oxidized to produce a surface that has low backscattering and low reflectivity for the 1 μm light. The inside edge of most of the baffles are serrated to reduce coherent diffraction from the edges. The baffles protrude ~10 cm into the tube, leaving a clear aperture through the tube of 1 m.

The vacuum chambers and equipment at the ends of the tubes are designed to operate at 10^{-9} torr. Ultra-high vacuum techniques are used to prevent optics contamination from residual hydrocarbons in the chambers. Two styles of chambers are used to house optics, both of which allow easy access to components during installation and maintenance. Together with the beam tubes, the total volume of each vacuum system is 10,000,000 liters, making them the largest high-vacuum systems in the world.

3 Detector design

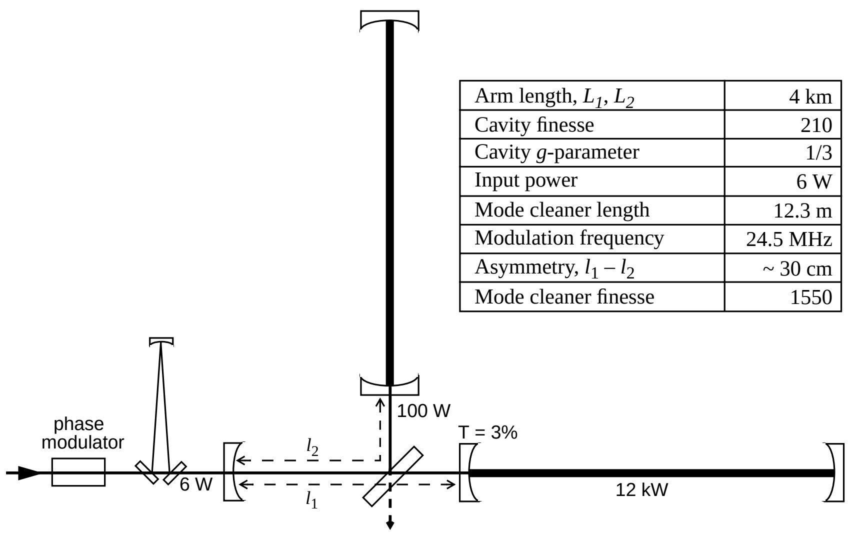
3.1. Strain Sensitivity

For designing the initial interferometers, LIGO has adopted a target strain sensitivity curve as shown in Figure 1. The interferometers are being designed to be limited by three noise sources across the detection band: shot noise at frequencies above 150 Hz; thermal noise at intermediate frequencies (40 – 150 Hz); and seismic noise at low frequencies (below 40 Hz). In general, other ‘technical’ noise sources (such laser amplitude or frequency noise, or photodetector electronics noise) are being controlled so that they each lie, in equivalent strain noise, at least a factor of 10 below the target curve at all frequencies.



3.2. *Interferometer configuration*

All three interferometers are power-recycled Michelson interferometers, with Fabry-Perot cavities in the arms, as shown in Figure 3. The 2 km interferometer in Hanford is chosen to have the same finesse as the 4 km versions. A single, triangular mode-cleaner cavity is used at the input to reduce higher-order mode content in the laser beam. The sensing of the gravitational wave signal is done using the ‘Schnupp’ modulation method, where the beam is phase-modulated at the input of the interferometer, and a path length asymmetry of order 30 cm is built into the Michelson.



Arm length, L_1, L_2	4 km
Cavity finesse	210
Cavity *g*-parameter	1/3
Input power	6 W
Mode cleaner length	12.3 m
Modulation frequency	24.5 MHz
Asymmetry, $l_1 - l_2$	~ 30 cm
Mode cleaner finesse	1550

Figure 3: Configuration of the initial LIGO 4 kilometer interferometers.

3.3. *Laser source*

In late 1995, the LIGO project made a decision to switch from using visible argon ion lasers to using Nd:YAG lasers operating at 1064 nm. Currently under development by Lightwave Electronics, Inc. of Mountain View, California, the laser uses a master oscillator-power amplifier design (Figure 4). The Lightwave Electronics model 126-700 single-frequency non-planar ring oscillator (NPRO) serves as the master oscillator. The power amplifier contains four discrete gain sections, each consisting of a single Nd:YAG element pumped by two 20 W (rated output) diode bars. The four gain sections are double-passed, using polarization rotation to select the second-pass beam at the output. The output will be ~10 W of TEM_{00} mode power, with an $M^2 < 1.1$ (less than 10% of the light in higher-order modes).

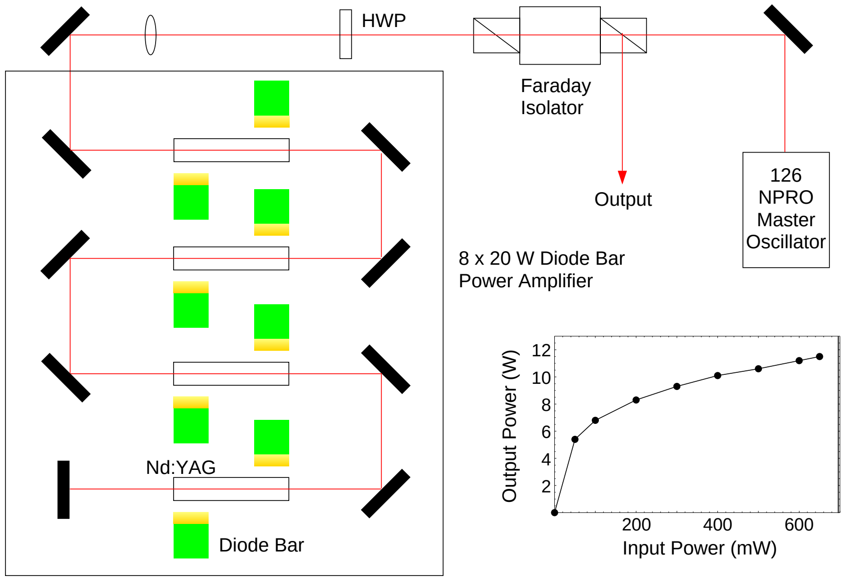


Figure 4: Design of the 10 W MOPA Nd:YAG laser being built by Lightwave Electronics, Inc. for the LIGO project. The master oscillator beam is double-passed through the amplifier (HWP is a half-wave plate).

This laser is imbedded in a pre-stabilized laser system, which is designed to implement the first stages of frequency and amplitude stabilization on the laser. The frequency is stabilized to a fused silica reference cavity at the $\sim 10\ \mathrm{mHz}/\sqrt{\mathrm{Hz}}$ level, using the thermal and piezo transducers built into the NPRO and a phase modulator located between the NPRO and the amplifier. Amplitude stabilization in the gravity wave band is implemented by actuating on the current supplying the amplifier's diode laser bars, taking the error signal from a photodetector sampling a portion of the light transmitted by the suspended mode cleaner. Some amplitude stabilization at the RF modulation frequency is also required, because the noise inherent in the NPRO and the noise introduced by the amplifier result in a laser beam whose amplitude fluctuations are above the shot-noise level around this frequency. This is accomplished by passing the beam through a resonant, 'filtering' cavity, designed to have a filter pole frequency of ~1.5 MHz, and thus an attenuation factor of nearly 20 at the modulation frequency.

3.4. Core optics

The large optical components, or 'Core Optics', in the interferometer consist of four test masses, a beamsplitter, and a recycling mirror (the 2 km interferometer also includes 2 folding mirrors which must meet requirements similar to those of the recycling mirror). The requirements for these components have been derived using a computer model of the interferometer which uses an FFT-based optical propagation code [2]. The model, based on original code provided by J.Y. Vinet and P. Hello of VIRGO [3], solves for the carrier and sideband spatial field distributions at various places in the interferometer. The code employs a fast convergence algorithm [4] and runs on a supercomputer.

Table 1: Partial listing of requirements for the LIGO Core Optics.

Physical Quantity	***Test Mass***		***Beam splitter***	***Recycling Mirror***
	End	***Input***		
Diameter of substrate, ϕ_s (cm)	25	25	25	25
Substrate Thickness, d_s (cm)	10	10	4	10
Mass (kg)	10.7	10.7	4.2	10.7
Nominal radius of curvature (m)	7400	14540	inf	15 km
Tolerance on radius (m)	absolute: ±220 matching: ±111	–1000, +145	> –720 km convex, > 200 km concave	– 100, +500
Figure error, central 8 cm (nm)	0.8	0.8	0.8	–
Surface microroughness (nm)	0.4	0.4	0.4	–
Surface absorption (ppm)	2	2	2	–
Bulk absorption (ppm/cm)	N/A	5	5	N/A
Internal mechanical frictional loss	$< 10^{-6}$	$< 10^{-6}$	$< 10^{-6}$	–

There are four components to producing a core optic: the substrate, substrate polishing, coatings, and metrology. An optics development program (called ‘Pathfinder’) has been underway in LIGO to evaluate the state-of-the-art in these areas, to initiate work to further the state-of-the-art were needed, and to identify companies with the ability to fabricate the LIGO core optics [5].

The optical homogeneity and mechanical of the Pathfinder (full-size) substrates have been shown to meet the requirements of the initial interferometers. Since the switch to 1064 nm, the optical absorption in fused silica has become a critical parameter, due to the deleterious effects of thermal lensing of transmitted beams in the beamsplitter and input mirrors. In order to counter to some extent the effect of thermal lensing (even with low-absorption material), the current design calls for polishing the recycling mirror with a radius of curvature about 50% larger (15 km instead of 10 km) than optimal for mode-matching *sans* absorption, in order to provide better matching for the sidebands in the presence of the thermal lenses. Fortunately, the VIRGO project has determined that Heraeus has a process which yields fused silica with ~5 ppm/cm absorption. Therefore Heraeus has been selected to supply substrates for the input mirrors and beamsplitters, and Corning for all others. Orders for approximately 40 blanks were placed in 1996, the quantity chosen to allow for spare finished optics and for any problems in the fabrication process.

Three companies performed best-effort polishing on the Pathfinder substrates: Commonwealth Scientific and Industrial Research Organization (CSIRO), General Optics (GO), and Hughes-Danbury Optical Systems (HDOS). Metrology of all polished substrates was performed at the National Institute of Standards and Technology (NIST). With care, measurements at < 1 nm level proved possible – reproducible features were seen and consistent comparisons were demonstrated at this level. The metrology indicated that polished surfaces with rms deviation (after removing focus and astigmatism) < 1 nm over ~20 cm diameter were produced by CSIRO and GO. In some cases, apparent deviations of ~ 0.5 nm were measured. Surface roughness measurements showed a microroughness of ~3Å for the CSIRO substrates and ~0.9Å for the GO substrates. Both GO and CSIRO have been selected to polish the core optics.

LIGO has been collaborating with Research Electro Optics (REO) in developing coating uniformity, with the goal of scaling REO's low-loss ion-beam-sputtered coating technology to LIGO diameters. To measure the coating thickness variations over long and short spatial scales, a technique has been developed that involves mapping the reflectivity of specially designed two-layer anti-reflection coatings and deriving a map of an individual layer through a least-squares minimization process. Single layer maps are then stacked in a coherent manner (worst-case assumption) to synthesize a predicted phase map for a high-reflectivity coating. This analysis has lead to iterations in REO's coating process, with subsequent improvements observed in the uniformity over long spatial scales. The results are encouraging that the uniformity requirements for the core optics are attainable.

3.5. Sensing and Control systems

There are 4 length and 12 alignment degrees-of-freedom in the interferometer that must be very close to their optimal values in order to maintain the strain sensitivity of the interferometer. The requirements for these degrees-of-freedom derive in general from two considerations in the presence of deviations from the optimal points: the degradation of the shot-noise limited sensitivity, and the sensitivity of the gravity wave readout to noise coupling terms. The requirements on the residual deviations of the length degrees-of-freedom are given in Table 2. The principal noise coupling mechanism is intensity noise of the laser appearing at the gravity wave readout when the interferometer is not exactly at the dark fringe.

The four lengths are sensed by demodulating the outputs of photodetectors, placed at various ports of the interferometer, at the phase-modulation frequency used on the input beam, as described in reference [6]. A digital control system is being designed that will digitize the four demodulator outputs (after passing through whitening and anti-aliasing filters) and perform digital filtering and signal mixing in a central processor. Control signals are output on DACs, with most likely all six interferometer optics receiving some length control signal. In addition, using the photodetector signal at the interferometer's reflected port, an analog servo path is used to stabilize the laser frequency to the final required level of $3\times10^{-7}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz.

Table 2: Requirements on the residual deviations of the four length degrees-of-freedom; k_l is the propagation constant of the laser and F is the finesse of the arm cavities.

Definitions	*Residual Deviation Requirement, rms*	*Mechanism*
$L_- \equiv L_1 - L_2$	$\left(\delta L_- + \frac{\pi}{2F}\delta l_-\right) \le 1\times10^{-13}$ m	Amplitude Noise Coupling
$l_- \equiv l_1 - l_2$	$\delta(k_l \cdot L_+) \le 9\times10^{-6}$ radian	Power Drop → Sensitivity loss
$L_+ \equiv L_1 + L_2$	$\left(\delta l_- + \frac{\pi}{2F}\delta L_-\right) \le 1\times10^{-9}$ m	Amplitude Noise Coupling
$l_+ \equiv l_1 + l_2$	$\delta l_+ \le 1.25\times10^{-10}$ m	Power Drop → Sensitivity loss

One of the challenges in sensing the lengths is developing a photodetector than can handle the high optical power that must all be converted into photoelectrons in order to preserve the shot-noise sensitivity. Following the work of the VIRGO group, LIGO has investigated the performance of indium-gallium-arsinide (InGaAs) photodiodes, a material which has both high quantum efficiency and high power handling capability. Tests have shown that the RF response, at small modulation depth, of a 2 mm diameter device remains linear up to an average incident power level of ~200 mW. The current design calls for 4-6 such devices to be used at the antisymmetric (gravity wave) port of the interferometer, with the power split equally between them.

Misalignments of the interferometer optics produce similar effects of degrading the shot-noise limited sensitivity and introducing noise coupling mechanisms [7]. In this case, the principal noise coupling mechanism is fluctuations of the input beam direction appearing at the gravity wave readout when the interferometer is not perfectly aligned. An analysis of these effects shows that in order to maintain maximum strain sensitivity, the angular orientations of the optics must be within 10^{-8} radian-rms of the optical axis. In addition, fluctuations in the input laser beam direction must be below $1.5\times10^{-14}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in angle and $2.8\times10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ in displacement for frequencies $f > 150$ Hz, in order that they not degrade the gravity wave sensitivity. Finally, the lateral offset of the laser beam axis from the optics' centers-of-gravity must be smaller than about 1 mm, in order that optical path changes produced by thermally excited angular fluctuations of the optics remain insignificant.

An automatic alignment system has been designed that discriminates between all angular degrees-of-freedom, and implements closed-loop servo control of all the angles to bring them within 10^{-8} radian-rms of perfect alignment. The alignment system uses the wavefront sensing technique to detect the mirror angles relative to the input laser beam. The sensing is done with quadrant photodetectors that detect small fractions of the interferometer beams used to detect the lengths; these sensors detect spatially asymmetric RF amplitude modulation on the light, due to phase gradients produced by misalignments. This technique was recently demonstrated on a table-top interferometer in a configuration very similar to LIGO, where all the mirror angles were sensed and controlled to perfect alignment [8].

3.6. Suspensions & Seismic Isolation

The basic seismic isolation design concept for initial LIGO of a stack of mass-spring oscillators has remained unchanged for some time, but the detailed design has advanced considerably recently due to the design work performed for LIGO by HYTEC, Inc. of Los Alamos, N.M. The key advance has been the development of a new spring design – a metal coil spring incorporating constrained layer damping. For the same load capacity, the metal spring is much softer than the older all-Viton spring, leading to increased isolation. The coil spring is constructed with multiple tubular layers; a high loss viscoelastic layer is sandwiched between an outer tube of phosphor bronze and sectioned-aluminum inner tubes; the ends of the coil are sealed with welded caps.

The isolation stack for a test mass has four legs, each leg composed of four layers of spring/mass filters; the masses of each leg element (stainless steel cylinders) and the number of springs in each layer are optimized to maximize isolation around 35 Hz. The projected performance of the stacks is shown in Figure 5.

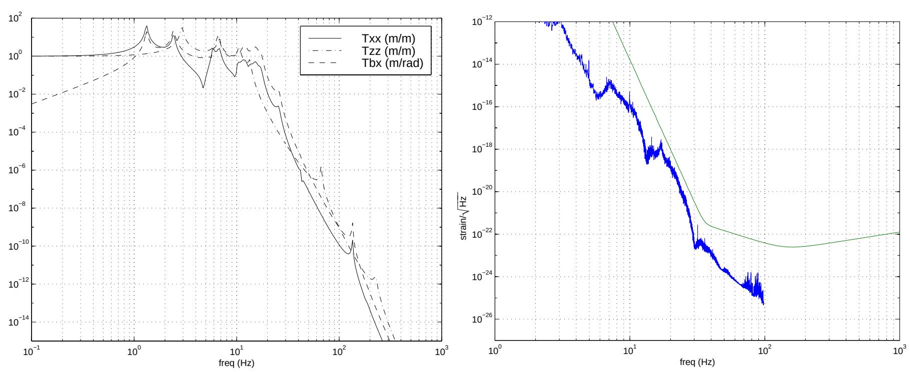


Figure 5: Left: Simulated transmissibilities (ground-to-pendulum suspension point) for horizontal-horizontal motion (along the optic axis) (T_{xx}), for vertical-vertical motion (T_{zz}), and for (ground) pitch-horizontal motion (T_{bx}). Right: Prediction for the ground noise-limited strain sensitivity (lower curve) for the initial 4 km interferometer using the stack model on the left and measured ground motion data at the Livingston, LA site; the prediction falls below the target sensitivity for initial LIGO (upper curve).

The seismic isolation system also includes an on-line, fine actuator system that is capable of compensating for micro-seismic disturbances at a frequency of 1/6 Hz, as well as for diurnal ground motions resulting from earth tides. The fine actuator is external to the vacuum, and uses piezoelectric transducers. The approach currently being pursued for reducing the micro-seismic amplitude is to measure the relative motion between the vertex and the ends of the arms, and to apply a feed-forward correction to the fine actuators located at the arm ends.

The top layer of the stack (the optics platform) supports the core optic and its suspension. The optic is suspended from a single loop of wire (Figure 6), giving a horizontal eigenfrequency of 0.74 Hz, and pitch and yaw eigenfrequencies of 0.6 Hz and 0.5 Hz, respectively. Displacement and angular control is afforded by magnet-coil actuators; magnets are attached to the optics through mechanical standoffs to decrease mirror strain-energy coupling to the magnets, and coils are attached to a suspension support structure on the optics platform. The four low-frequency eigenmodes can be locally damped using these actuators and optical sensors that are integrated with the coil assemblies. In order to avoid the stresses (and resultant stress-energy release) inherent in a bolted assembly, the suspension support structure is welded and annealed.

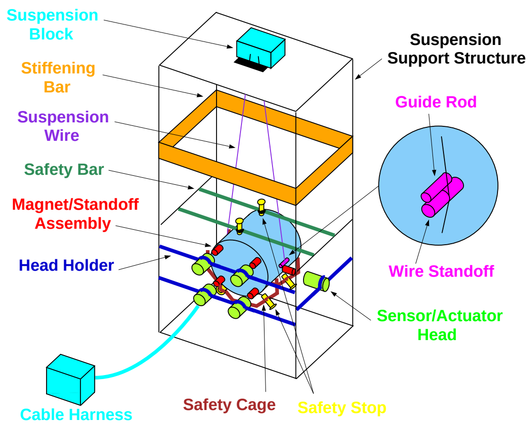


Figure 6: Schematic illustration of the suspension assembly for a core optic. The support structure is welded tubular stainless steel. The suspension wire is 0.31 mm diameter steel music wire, giving a fundamental violin mode frequency of 340 Hz..

3.7. Physics Environment Monitoring System

In addition to the interferometer(s), each LIGO site contains a Physics Environment Monitoring System (PEM) for measuring environmental disturbances that could produce spurious signals in the gravity wave readout. The PEM system consists of an array of mostly commercial transducers: seismometers, accelerometers, magnetometers, tiltmeters, microphones, RFI monitors. The system also contains various stimulation sources, such as force shakers and loudspeakers, for characterizing the sensitivity of the instruments to external disturbances.

The primary use of the PEM data will be as a veto in burst searches, reducing the number of candidate events for coincidence analysis between interferometers. The data may also be useful for correlating external disturbances with the gravity wave readout, possibly leading to a regression of measured disturbances from the gravity wave channel which would increase the signal-to-noise ratio for detection. In addition, determining the sensitivity of the interferometer to environmental disturbances will be invaluable to the development of future interferometer subsystems.

3.8. Control and Data System

The Control and Data System (CDS) performs supervisory control for and collects data from the interferometer(s), the vacuum system, and the physics environment monitoring system. Hardware is based on standard VME crates and modules; the Experimental Physics and Industrial Control System (EPICS) is used for supervisory software control. Timing is derived from the Global Positioning System (GPS), and data is transported from points in the interferometer to the acquisition system through a reflected memory network.

Data sample rates range from 2 – 16,384 samples per second. The data collection rate from both sites (all three interferometers) is estimated to be ~8 Mbytes/second, made up of approximately 400 channels per interferometer and 200 channels per site, as indicated in Table 3. The data will be recorded to tape using a "frame-builder" to write data in the frame format originated by VIRGO, and currently adopted by all gravitational wave projects.

Table 3: Estimated data collection rate for the initial LIGO detector.

System	***# Channels/IFO***	***Total Rate, kB/s***
Length Sensing & Control	43	1,574
Alignment Sensing & Control	132	1,430
Suspensions	100	2,025
Prestabilized Laser	12	674
Input Optics	63	804
Physics Environment Monitor	202	1,576
Total	552/IFO	8.1 MByte/sec

4 Plans and Schedule

Installation of the detector at the Hanford site is due to begin in the spring of 1998, at which time the facilities there will be complete. The 2 km interferometer is planned to be completed first; it should see 'first light' in mid-1999. All three LIGO interferometer are scheduled to be operational by the end of 2000, and working at their design sensitivity by the end of 2001. The first LIGO data run (LIGO I) will occupy the years 2002-2003, with the expectation of at least one year of integrated 'live time' (all three interferometers taking data) in that span.

Beginning in 2004, improved subsystems and advanced interferometer configurations will be installed in stages, in order to incrementally improve the strain sensitivity in selected bandwidths. One possible sequence of such improvements is outlined in Figure 7. A program of advanced research and development has been initiated by the LIGO project and members of the LIGO Research Community (LRC) to work on the problems associated with improving on the initial LIGO sensitivity.

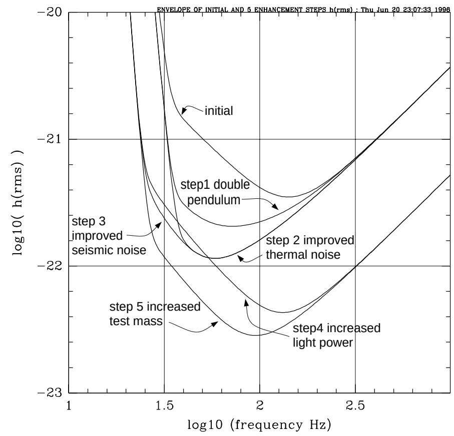


Figure 7: The improvements in $h_{rms} \equiv h(f) \cdot \sqrt{f}$ associated with the steps outlined in the LIGO Advanced R&D proposal [9]. The logic of the steps is determined by the assumption that compact binary coalescences are the most likely source to be detected, hence the importance of improving the sensitivity near 100 Hz. The improvements associated with the double suspension, reduction in the thermal noise and increase in the test mass (steps 1, 2 and 5) are tightly coupled.

Acknowledgments

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