

LIGO Renewal (2002-2006) Proposal DRAFT
Proposed Work in
Campus based research activities
At the 40 Meter Interferometer Facility

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In order to prototype the Advanced LIGO optical configuration and controls, and study its performance, a fully instrumented suspended-mass interferometer is needed. The 40 Meter facility is well suited to this task. (The LIGO observatory sites would be an even better place to do this prototyping, but they will be in the midst of the LIGO science run and must be left undisturbed while Advanced LIGO is being developed). The 40 Meter facility is being upgraded in order to perform these critical prototyping tasks in the years before the installation of Advanced LIGO at the observatory sites.

Several key elements of the proposed optical configuration for Advanced LIGO are novel, and therefore require careful prototyping. In addition to the Initial LIGO configuration (consisting of a pre-stabilized laser, 12 meter input mode cleaner, the core suspended-mass power-recycled Michelson interferometer with Fabry-Perot arms, and Pound-Drever style MIMO length- and angular misalignment sensing and control plants), the scheme calls for:

- the addition of a seventh mirror for signal recycling with a detuned signal cavity;
- a pair of phase-modulated RF sidebands with frequencies made as low and as high as is practically possible (so that little of the low-frequency RF sidebands see the signal mirror, while one of the high-frequency RF sidebands has maximal sensitivity to that mirror position), and the use of double demodulation to produce the error signals;
- a short output mode cleaner to filter out all RF sidebands and higher-order transverse modes (allowing only the carrier and signal sidebands to pass);
- DC readout of the gravitational wave signal; and
- offset-locked arms to permit a controlled amount of arm-filtered carrier light to exit the dark port of the beam splitter.

These elements have been chosen after the successful tests of several different table-top interferometers, but no one interferometer has employed them all, with any degree of fidelity to the proposed configuration. As is now well appreciated, all elements of a complex optical configuration such as the one proposed for Advanced LIGO interact with one another in non-trivial, often non-intuitive ways. Thus, a full-scale systems test of all features of the configuration, in a suspended-mass interferometer, is essential. The Caltech 40 Meter interferometer facility is a natural place to perform such a test, because of its well-developed and appropriate infrastructure, and its proximity to the Advanced LIGO controls engineering team.

The primary role of the upgraded 40 Meter interferometer facility will be to perform a full systems prototype of all aspects of the Advanced LIGO optical configuration, the interferometer sensing and control, and gravitational wave signal extraction. Special attention will be paid to minimizing any extrapolation of the prototyped system to the LIGO facilities, by maximizing the fidelity of the tests. Cavity finesses, as determined by mirror transmittances, will be exactly as planned for Advanced LIGO. The full interferometer length and angular misalignment sensing scheme, including all control topologies, RF frequencies, electronics, *etc.*, will be as close as possible to what will be employed at the sites.

It is expected that the currently proposed Advanced LIGO optical configuration and controls scheme will evolve as more thought, effort, modeling, and prototyping continues over the next few years. In particular, a limited test of many of the features of the configuration will be prototyped at the Glasgow 10 meter suspended mass interferometer within the next two years. The 40 Meter team will closely follow, and contribute to, this progress. If required, any changes to the planned configuration and control scheme will be implemented in the 40 Meter prototype. The highest priority will be placed on the highest fidelity of the prototyping to the actual scheme to be implemented at the sites. After the 40 Meter interferometer is fully working, commissioning and testing will undoubtedly uncover a variety of problems or poor optimization in the implementation. We expect that at least one iteration of the prototyping will be required before the final scheme is installed at the sites. This is reflected in the schedule.

The interferometer being planned for the 40 Meter laboratory shares the following features with the current Initial or Advanced LIGO design:

- There will be an Initial LIGO 10 watt pre-stabilized laser (PSL). No tests of thermal effects associated with a much higher-powered laser will be possible (or meaningful) at the 40 Meter, due to the shorter cavity lengths and correspondingly smaller beam transverse size.
- There will be a 12 meter suspended mass input mode cleaner and associated control system (essentially identical to the current LIGO design, and only a bit shorter than the mode cleaner length proposed for Advanced LIGO).
- LIGO uses suspended mirrors for mode matching and steering from the mode cleaner into the main interferometer; at the 40 Meter, these functions will be performed by fixed lenses and motorized mirrors, placed in vacuum on existing seismic stacks.
- The main interferometer will contain seven suspended mirrors (two ITM's, two ETMs, a beam splitter, power recycling mirror, and signal recycling mirror). The optical quality of the glass and the coatings, and the transmissivities, will be identical to those proposed for Advanced LIGO (with fused silica).
- The mirror suspensions will, initially, be identical to the Initial LIGO small optics suspensions (SOS) for all mirrors except for the ITMs and ETMs. These latter mirrors will be suspended from scaled up versions of the SOS's. As in Initial LIGO, there will be five OSEMs (optical shadow sensors and magnetic actuators) per suspension. The opportunity to test scaled-down versions of the Advanced

LIGO multiple pendulum suspensions at the 40 Meter will certainly exist; but the 40 Meter vacuum chambers will not be able to accommodate full-scale prototypes without major modifications.

- All suspensions will be controlled with digital suspension controllers.
- Phase modulated RF control sidebands will be applied to the beam in air, before the mode cleaner, as is anticipated for Advanced LIGO. This will include RF modulation, distribution, sensing, and mixing at ~ 180 MHz.
- The full interferometer length and alignment (wavefront) sensing and control will be implemented in a manner which most closely resembles the system intended for the sites, in every respect (overall controls topology, optics, electro-optics, and electronics).
- All mirrors will be monitored with optical levers. All output ports will be monitored with cameras, quadrant photodiodes, shutters, *etc.* A rudimentary "environmental monitoring" system (seismometers, magnetometers, microphones, thermometers, *etc.*) will be employed.
- Initial LIGO versions of the Data Acquisition system, Global Diagnostics System, local networking and inter-process communication, EPICS-based control and monitoring, and other key hardware and software systems, will be implemented. The 40 Meter laboratory will be used for any needed development of these systems for Advanced LIGO.

The optical configuration for the upgraded 40 Meter interferometer is shown in Fig. 1, where cavity lengths, optic radii of curvature, and beam spot sizes are indicated. A detailed optical layout is given in Fig 2. The predicted strain noise is shown in Fig. 3. [NOTE to editor: this section is too long; any or all of these figures can be omitted.]

As discussed below, the 40 Meter interferometer laboratory differs from the sites in many important ways. Because of the much shorter arms, the 40 Meter interferometer is, of course, relatively insensitive to expected gravitational wave strains. The laboratory has other constraints which limit its ability to prototype all aspects of the Advanced LIGO design. Despite these, it is entirely suitable for prototyping all aspects of the Advanced LIGO optical configuration, and the shortcomings mentioned below do not impact heavily on the fidelity and validity of the planned tests.

The smaller vacuum chambers at the 40 Meter facility will not accommodate full-scale prototypes of the active seismic isolation systems or multiple pendulum suspensions; these require the full-sized chambers available at the LASTI facility at MIT. The small size of the beams resonating in the 40 Meter optical cavities will not provide a useful test of the thermal noise in LIGO test mass optics. Thermal compensation schemes to deal with the high laser powers at Advanced LIGO, do not require a full suspended-mass interferometer and can be done in smaller laboratories (although the 40 Meter will be available if tests there are desired). Similarly, for the testing of silica fibers bonded to the optics.

The 40 Meter interferometer facility is limited by the size of its vacuum envelope. The much shorter arms means that, for a given cavity finesse, the arm cavity pole is much

higher than at LIGO. This is not expected to have any significant impact on the control of the interferometer (although the sensitivity to gravitational wave strain is reduced by a factor 100 compared to LIGO). The shorter power recycling cavity length means that the lower frequency RF sideband referred to above must be higher in frequency than in LIGO, in order to resonate in the 40 Meter power recycling cavity. This makes the controls problem a bit harder, since the separation between the control signals for the power and signal recycling cavities is poorer. Thus, the test of the control of these cavities is a conservative one: if it can be accomplished at the 40 Meter (which should not be a big problem), it will be only easier at LIGO.

The 40 Meter laboratory has higher environmental noise than at Hanford and Livingston, due both to higher seismic motion and to human activity during the daytime. This might have a negative impact on the ability of the interferometer to acquire lock, which is one of the more important tests of the control scheme. The seismic isolation stacks at the laboratory, which were early prototypes for the passive stacks used presently at LIGO, are well tested and perform well. They employ highly damped, but stiff, viton springs; LIGO stacks use less well damped, but also less stiff, metal springs. The stiffer springs limit gravitational wave sensitivity to frequencies above 100 Hz. The higher damping at the 40 Meter means that they amplify seismic motion less than do the damped metal spring stacks, at the low frequencies (~ 1 Hz) where the control system operates in order to acquire lock. In addition, the 40 Meter laboratory rests on a single, short-length concrete slab, so the "microseismic" differential motion which makes acquiring arm lock at LIGO a challenge, is absent. Thus, modeling indicates that the higher environmental noise at the 40 Meter laboratory should have minimal impact on lock acquisition. Nonetheless, any reduction of the effects of environmental noise on the interferometer are well worth the effort. Thus, we will be installing (at some expense and effort) a system of active seismic isolators between the passive seismic stacks supporting the test masses, and the laboratory floor. Modeling indicates that this will reduce the environmental noise driving the test mass mirrors to levels below that of the present LIGO.

The schedule for the 40 Meter prototyping activity is driven, and limited, by the availability of Advanced LIGO R&D engineering and physicist support; the key personnel are heavily committed to Initial LIGO commissioning. The schedule must remain flexible, in order to accommodate changes resulting from continued progress in the design of the Advanced LIGO configuration and controls. The primary milestone is that at least one iteration of a full systems engineering test shall be completed before the end of the Initial LIGO science run in 2005.

During FY01, the 40 Meter laboratory will complete the upgrade of the facility itself. The building has been renovated to accommodate increased interferometer floor space for interferometer sensing optical tables, a new 12 meter mode cleaner, and many racks of control electronics. A new operator control room, and new clean room changing area, have been constructed. Leaks from the roof and from building entrances will be repaired. A new output optic chamber, with new seismic isolation stack, will be installed. A new vacuum envelope for the 12 meter mode cleaner will be installed. A new active seismic isolation system will be installed under the test mass chamber passive stacks. A new

EPICS-based vacuum control system has been built and will be commissioned. A 10 watt pre-stabilized laser will be installed.

In FY01, the mode cleaner optics will be procured, polished, coated, and tested. SOS suspensions will be under construction, and the first optics can be suspended. We should have the opportunity to commission the new mode cleaner. Throughout FY01, and into FY02, the core optic glass and suspensions will be procured, polished, coated, and tested, and hung.

In FY02, the design of the Advanced LIGO control electronics should be ready for prototyping. By the end of FY02, the entire interferometer sensing and control scheme will be assembled, and full-scale testing can begin. At this point, involvement by LIGO interferometer physicists and engineers, and LSC members, will be most needed.

The development, testing, and final prototyping of an Advanced LIGO optical and control configuration at the 40 Meter facility will make the installation and commissioning of Advanced LIGO at the observatory sites as smooth and quick as possible. It will benefit tremendously from the close proximity to the Caltech-resident LIGO mechanical, optical, and electrical engineering staff, as well as from the rich intellectual environment of the Caltech campus. Perhaps most importantly, it will facilitate the training of yet another generation of gravitational wave interferometer physicists, including graduate students, undergraduates, and visitors.

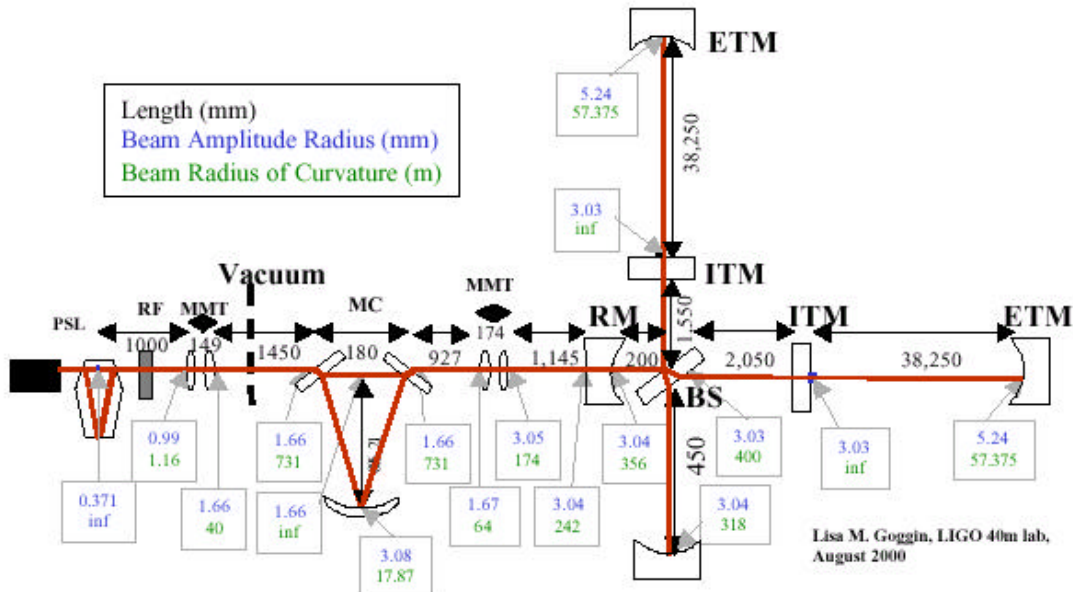


Figure 1: Optical configuration of the 40 Meter interferometer for prototyping Advanced LIGO. Cavity lengths, beam spot sizes, and optic radii of curvature, are indicated.

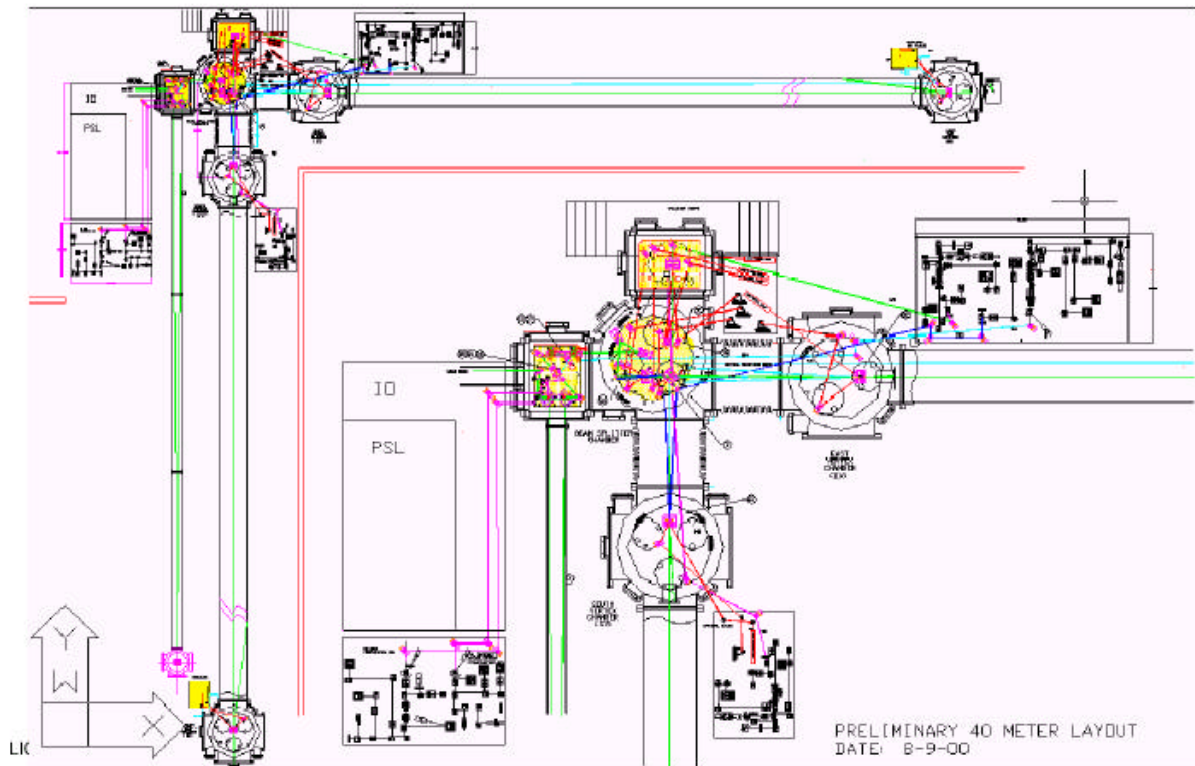


Figure 2: Detailed optical layout of the 40 Meter interferometer, showing the vacuum chambers and beam tubes, optical tables for the PSL and for interferometer sensing, main IR laser beam (green), beams exiting at the ports, and auxiliary beams (optical levers).

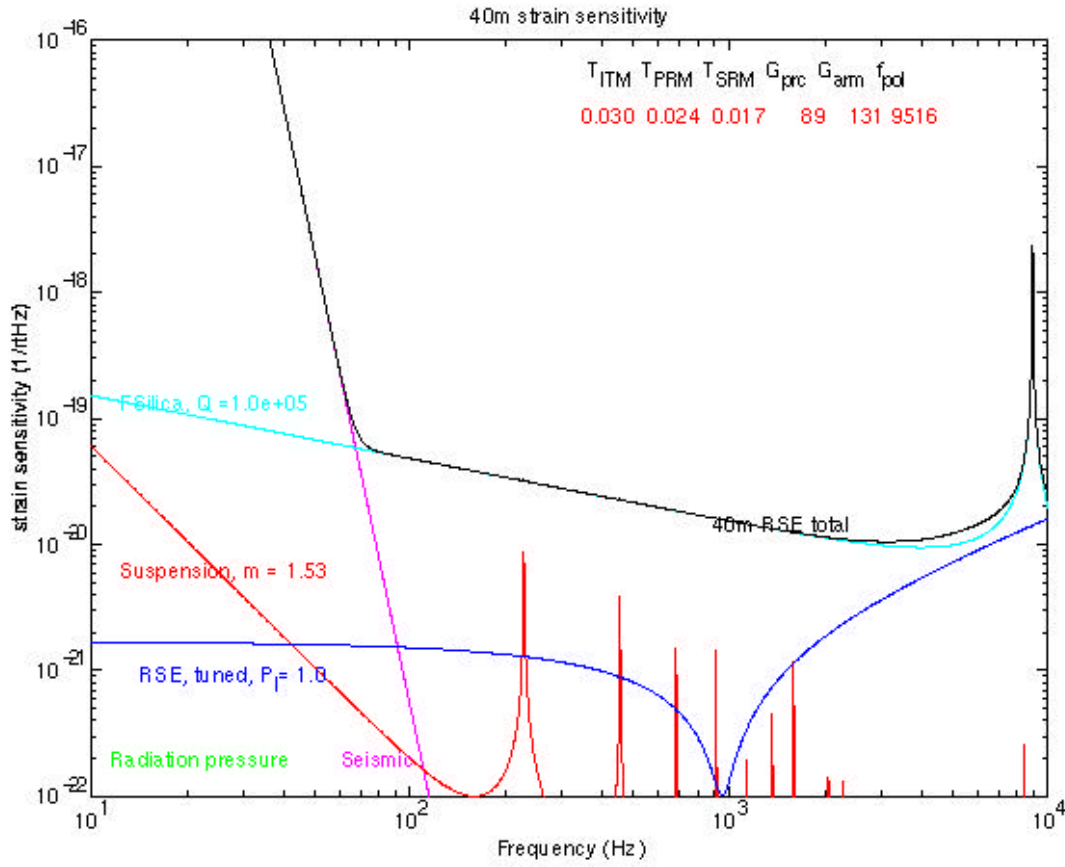


Figure 3: Predicted strain sensitivity of the 40 Meter interferometer, including all known fundamental noise sources. Cyan: thermal noise of the test masses. Red: suspension noise, including violin modes. Magenta: seismic noise. Blue: shot noise with 1 watt of input power. Green: radiation pressure (too low to be seen on this plot).