LIGO II System Requirements Meeting Summary

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Background and Motivation

The LIGO II schedule, derived from the White Paper milestones, calls for a draft LIGO II System Requirements document to be developed for review this summer. This document will guide the development of requirements for the LIGO II subsystems and will present a formal opportunity and framework for the many design tradeoffs.

Since the submission to NSF of the conceptual documents describing LIGO II, significant progress has been made in R&D and in estimates of noise sources. In order to properly incorporate the latest R&D information, and new noise estimates, the LIGO Laboratory requested that a meeting be held to review and discuss the LIGO II Reference Design presented last fall. The goal of this meeting was to recommend any changes in parameters, program strategy, and calculations or estimates to be included in developing the requirements document.

The meeting was led by Peter Fritschel, who will take the lead in preparing the System Requirements. It was attended by the leadership of the relevant parts of the LSC. The Lab was represented by those responsible for preparing the LIGO II plan. The leaders of the R&D tasks most closely related to the tradeoffs to be discussed (thermal management, mechanical Q, sensing, etc.) were also included. The meeting participants were:

Peter Fritschel, LIGO Laboratory, LIGO II System Requirements Document lead author
Gary Sanders, LIGO Laboratory Deputy Director, LIGO II Proposal lead author
Dennis Coyne, LIGO Laboratory Chief Engineer
Rainer Weiss, LSC Spokesman
David Shoemaker, LSC Suspensions Working Group Chair
Eric Gustafson, LSC Lasers and Optics Working Group Chair
Ken Strain, LSC Advanced Configurations Working Group Chair
Jordan Camp, LIGO Laboratory Sapphire Development Task Leader
Mike Zucker, LIGO Laboratory Thermal Compensation and Photodetector Development Task Leader
Peter Saulson, LSC

The meeting produced several significant recommendations to guide the work in developing the System Requirements and the greater LIGO II proposal. It is our intention to circulate this document to the Lab and LSC for comment. The overall System Requirements and revised LIGO II Reference Design will be presented to the August LSC meeting for discussion.

Upgrade Approach:

The recommended strategy is to make the first two upgraded interferometers 'broadband' in response, and to facilitate a tunable, narrowband response for the final interferometer. The broadband instruments would have a fixed signal-recycling mirror, tuned once to optimize detection of neutron star binary inspirals; these are thought of as the 'discovery'interferometers. The narrowband instrument would also have a fixed transmission SR mirror, but it would be chosen for better higher frequency response; the tuning range would be roughly 500Hz - 1kHz. The LHO 2km interferometer would be extended to 4km arms for the narrowband interferometer. This configuration is a recommended goal, to be accommodated in the design and program plan. However, the final decision to upgrade the last interferometer at all or whether to implement it as a narrowband instrument will be made later in the program.

The recommended upgrade schedule scenario is:

1. Install & commission LLO 4K: begin in vacuum system 1/2005 end 6/2006
2. Install & commission LHO 4k & 2->4k: begin. 7/2006 end 12/2007

18 months are planned to implement the first interferometer prior to beginning work on the other two. Thus, the first instance can serve as a prototype for the later two (18 months is the minimum period thought to be feasible for this purpose), and the LHO interferometers can continue to collect data in coincidence with non-US detectors (this plan must be coordinated with the other projects). There was some discussion about whether the first interferometer is upgraded all at once (complete replacement of hardware at the beginning), or in stages (replacing only some parts of the existing interferometer at a time, and testing their performance using the rest of the interferometer). The recommended program strategy is the complete upgrade of the first interferometer as this permits full system shakedown.

Interferometer Design

We recommend maintaining the reference design concept (for the broadband (BB) instruments) as a signal recycled interferometer with sapphire test masses. We identified a fallback design with fused silica mirrors (nominally with signal recycling) in the event that sapphire development is not sufficiently advanced for input test masses for the first upgraded interferometer. We also looked at the design of the narrowband (NB) instrument. The nominal parameters of these designs are listed below.

The sensitivities of the BB designs are not very different, and do not strongly support the sapphire choice (given that it is technically much riskier than silica). The sensitivities for sapphire vs. silica approach each other after a combination of tweaking the silica design, and a change of parameters for the sapphire design (see below). Other optics and materials parameters not listed below are set as we discussed at the meeting and the complete set of Bench parameters will be made available.

	Sapphire BB	Silica BB	Sapphire NB
P in	125 W	80 W	125 W
T_itm	0.5%	3%	2%
T_srm	0.05	0.3	2%
phase_srm	0.09	0.5	varies
mass	30 kg	30 kg	10 kg
TM beam size	5cm	5 cm	5 cm
TED	9x	6x	12x
TRD	same	10x	1.3x
NBI range	169 Mpc	162 Mpc	
Stochastic	3.1e-9	1.7e-9	

TED is thermoelastic distortion, and is given relative to the LIGO I level (recall that in LIGO I, TED is not significant - roughly 10x smaller than TRD). TRD is thermorefractive distortion, and is given relative to the LIGO I level.

Each design has been (roughly) optimized for best handling of thermal loading. The signal recycling for the BB interferometers has been optimized for maximum inspiral range. For future sensitivity comparisons, the capability of calculating black hole-black hole inspirals should be added to Bench.

For the sapphire design, the thermal distortion looks like it is manageable by just choosing the proper RM figure. For the silica design, we would need the active thermal compensation to work. The sensitivity of the sapphire NB interferometer, within its tuning range of ~500-1000 Hz, peaks at about 1e-24/rtHz for a given tuning. The sensitivity of the silica design has been increased a little by:

1. using 3e7 for the Q (vs 2e7)
2. increasing the beam size to 5cm (same as for sapphire design; might as well use the large optic size)

On the other hand, the sensitivity of the sapphire design has come down because we increased the coefficient of thermal expansion from 5e-6 to 6.65e-6 (the latter number was found in Eric's E-O Handbook). We have realized that this parameter varies quite a bit in the literature (10's of %), and of course the thermoelastic noise is very sensitive to it. We also need to nail down the specific heat and thermal conductivity of sapphire for the same reason (though there is less variation of these parameters in the literature). Clearly this uncertainty must be resolved in our favor if sapphire is going to continue to be pursued for the broadband design. Eric is looking into it further, and is mobilizing his group to get measurements.

For the narrowband interferometer, sapphire still provides about a factor of 2 better strain sensitivity over the tuning range, compared to silica.

Both BB designs exceed the 125 Mpc/interferometer sensitivity mark that would give LIGO II (3 interferometers) a 200 Mpc range.

Ken has looked at using even larger beam sizes, using Melody to evaluate the stability of the system with thermal loading. Preliminary results indicate that a 6cm beam size appears to be tenable for sapphire, for which the inspiral range is 197 Mpc. For silica, the same level of stability is reached with 5.4 cm spots and 80 W of input power; this design gives an inspiral range of 168 Mpc. Thermal handling is better managed in this silica design by increasing the arm cavity finesse (1% ITMs) and RSE factor.

A more conservative silica fallback design could be made, where we would use:

- smaller masses (16 kg)
- smaller beam sizes
- round fibers (wouldn't matter much, given the higher radiation pressure)

The technical difficulties particular to the silica design are:

1. large size: can we get the material (35cm diam x 14cm)? can it be polished and coated?
2. Q value: can we count on 3e7 ?
3. Need active thermal compensation to work well

The technical difficulties particular to the sapphire design are:

1. Coatings: experience to date not good (birefringence problems?)
2. Substrate birefringence; can we pass through substrate ?
3. Substrate nonuniformity; must correct for in polishing; need to do at least 3x better than what has been achieved
4. Lack of experience with polishing (figure & microroughness)
5. Thermoelastic noise

Active thermal compensation may be needed with the sapphire design also if the absorption cannot be kept at the 40 ppm/cm level.

Subsystem-By-Subsystem Design Concepts And Issues

SEI (Seismic Isolation)

Cut-off frequency. One method of choosing this is put it at the frequency where the strain sensitivity transitions from being limited by internal thermal noise to being limited by radiation pressure or suspension thermal (or any other noise that falls faster than the internal noise). The argument can be made that the sensitivity below this break point is lost quickly enough that it is not worth preserving. For all the designs we looked at, this break point is higher than 10 Hz, and is more like 20 Hz.

Another consideration are potential technical break-points where the implementation gets easier or harder. Once the seismic choice is made, the issue of cut-off frequency will be revisited with these thoughts in mind.

HAM Isolation

The requirement on this will most likely be relaxed from its present value. For the MC mirrors (which gave the present requirement), the radiation pressure fluctuations are slightly more than a factor of 10 above the SEI requirement. Some first estimates of the PRM and SRM sensitivities also suggest that they don't need as much isolation as previously conceived.

Suspensions

Fibers are recommended to be fused silica ribbons (1:10 aspect ratio), with circular fibers as a fallback (yielding ~2x higher noise). The baseline is a quad pendulum for BSCs (driven by the needed filtering of the vertical local sensors); and a triple pendulum for the HAMs. Active damping of modes is the baseline approach, but passive eddy current damping is also being pursued. For HAM suspensions, either much quieter local sensors are needed, or passive damping will need to be implemented. There is concern about how to achieve uniform tension in the 4 fibers.

Laser

The baseline power at the laser output is retained at 180 W. The power could drop to 120 W if the silica design is adopted.

Input Optics

The mode cleaner length is recommended to be kept short (~15m) for the baseline. Arguments for better frequency stability would have to be in the context of a complete frequency noise sensitivity and stabilization analysis. The ability to tune the SRM with a zero-crossing error signal (for the one tuneable interferometer) is also not a strong enough argument for such a change.

Active Thermal Compensation (ATC)

With the thermal optimization of the sapphire design, ATC may not be needed, but the bulk absorption of the material would have to be under control. For the silica design, we would rely on a factor of 10 compensation, which looks to be achievable with a ring heater alone.

Interferometer Sensing & Control

There are several sensing schemes to choose from. It is clear that we need to identify a candidate complete sensing scheme (e.g., picking and choosing from the various ideas developed in the benchtop experiments or otherwise proposed), and perform a first level of analysis on it.

For the GW channel readout, the idea of offset locking/DC readout looks very attractive and will be pursued with some additional calculations. Its obvious defect -- sensitivity to laser power noise -- looks to be inconsequential; the power stability requirement driven by technical radiation pressure is much more stringent (see below). The DC readout would be done with an output mode cleaner, so that the junk light competing with the local oscillator light would be limited only by the TEM00 contrast defect. The design of such a mode cleaner looks relatively simple because it does not have to pass RF sidebands, and has a relatively clean TEM00 mode to lock on.

Sensing of the SRM will be done without the ability to tune the RF frequency (short input mode cleaner), and so in the NB interferometer case, tuning will need to be changed by locking off the zero point of the error signal.

Given the two BB interferometers and one NB interferometer scenario outlined above, a variable reflectivity SRM is not required and thus we do not recommend including it in the baseline design.

Other Issues

Radiation Pressure

Technical radiation pressure will be a primary noise source at low frequencies. The effect goes as 1/f^3 - two poles from the mass inertia, one from the optical filtering. Assuming the input light can be stabilized to the shot noise in 30 ma all the way down to 10 Hz (RIN of 3e-9/rHz), the strain noise for 30kg masses, 800kW in the arms, 1% power imbalance between the arms (with relatively large uncertainty as to what can be achieved), is: 4e-23/rHz, which is a factor of about 2 lower than our reference design (falls more quickly than any of the other noise sources though).

Testing

Two ideas came out of this discussion:

The LASTI prototype would not pursue high displacement sensitivity as had been proposed. Instead, such a measurement would be put off to the first upgraded interferometer described above. Similarly, the 40m should not be committed to achieving the LIGO II phase sensitivity.

The PSL & mode cleaner is the largest subset of the full interferometer that can be tested in a campus laboratory at the full scale and with the actual hardware, and so it could be tested as such. Nearly all the site testing done on the LIGO I PSL and mode cleaner should be done instead in the lab. LASTI seems to be the best place to do such an integrated test if it can be accommodated in the scope of the primary LASTI tests.

With the avoidance of 'heroic' noise testing on lab prototypes, emphasis is put on benchtop-scale testing (and associated modeling) of particular noise contributors (eg, Q testing; creep/acoustic emission tests).