LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Review Report
Interferometer Sensing and Control Conceptual Design

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1 Executive Summary

The Interferometer Sensing and Control (ISC) Conceptual Review was held on April 9. 2008. The requirements are described in T070236-00, whereas the conceptual design can be found in T070247-00. At the review the following presentation was given: G080255-00.

We consider the ISC conceptual review overall a success and recommend that the ISC team go forward to working on the preliminary design. In a few instances we feel additional work is needed. A set of action items and recommendation follows. All recommendation should be addressed by the time of the preliminary design unless specifically mentioned otherwise.

1.1 Stable Recycling Cavity Decision

A decision has been made to implement stable recycling cavities in advanced LIGO. The unstable design in initial LIGO was responsible for increased sensitivity to thermal heating, for fairly large imbalances between the upper and lower RF sidebands, and for increased noise couplings due to imperfect overlap. The downside of a stable configuration is the increased role of astigmatism due to the beamsplitter wedge and the off axis beam reduction telescopes. However, we feel that having only stable optical modes propagating in the recycling cavities is a significant advantage. We welcome this decision.

1.2 Seismic Platform Interferometer

An important step in locking the long arm cavities is the seismic platform interferometer (SPI) which was not ready for review. The seismic platform interferometer is needed to reduce the relative mirror velocities between end and corner stations, so that lock can be achieved using the limited force actuators.

Action item: Hold an independent review during the summer of 2008.

1.3 Modes of Operations

The conceptual design lists no less than 6 modes of operations. This seems too many in view most of them give no substantial advantage but have significant downsides. Operational mode 0 is the initial LIGO configuration and could be used as a stepping stone to the fully recycled configuration. However, no details are given in the design. Mode 1b is a broadband configuration which has good sensitivities in all frequency bands. Furthermore, it is non-detuned, doesn't require imbalanced RF sidebands and has in general lower noise couplings than detuned modes.

Action item A: Concentrate on developing a preliminary design for sensing and controls of mode 1b only (non-detuned broadband resonant sideband extraction).

Action item B: Commission a study to investigate the trade-offs of using mode 0 as a stepping stone during commissioning. This should be completed by fall 2008.

1.4 Alignment Sensing and Controls

The alignment sensing and controls system is a complex system. It currently lags the design of the length sensing and controls system. More work is needed to refine the alignment sensing matrix, to identify a good error signal for common ITM misalignments and to develop a compensation network to cancel the Sidles-Sigg angular instability at high power. We expect the Enhanced LIGO project to lead the effort in high power investigations.

Action item: Allocate more resources to work on alignment sensing and controls in order to keep pace with the length sensing and controls. The controls topology needs to be worked out in full detail by the time of the preliminary design.

1.5 Environmental Couplings

Several environmental couplings have been identified that either limit or come close to limiting the initial LIGO sensitivity. These include seismic, acoustic, magnetic and RF couplings. The interferometer sensing and controls system is directly effected by vibrational coupling at the sensing tables, magnetic and RF coupling to the ISC electronics and, inside of the vacuum system, through vibrational modulation of scattered light (direct or up-converted through fringe wrapping). Even though advanced LIGO is significantly different in design, we would like to see a more focused effort to incorporate the lessons learned in initial LIGO.

Action item: Demonstrate by the time of the preliminary design that sufficient effort has been made to explicitly incorporate the lessons learned in initial LIGO with environmental couplings.

1.6 Software Development and Testing

The feedback compensation network which keeps the differential arm cavity length on resonance is part of the gravitational wave readout. Having a full understanding of the corresponding computer code is crucial in a convincing detection of gravitational waves. In initial LIGO the characterization of the length sensing and controls software is not well documented. This needs significant improvements to reach the level of scrutiny which is applied to the astrophysical analysis code.

We understand that the current ISC team consists of very few software persons. We recommend that more resources be actively recruited from the detector characterization group.

Action item: More resources have to be allocated to program, test and validate crucial software pieces. In particular, the scrutiny and documentation of software paths which are part of the gravitational wave signal readout have to be on a similar level as currently practiced by the data analysis groups. Algorithms have to be analyzed for validity, performance and limitations. All testing has to be documented.

2 Technical Scope and Issues

2.1 Scope

The Interferometer Sensing and Controls system is responsible for bringing the optical resonators into a mode of operation suitable for detecting gravitational waves. This includes the longitudinal and angular degrees-of-freedom of the input mode cleaner, the main interferometer and the output mode cleaner. It includes photodetectors, demodulation electronics, analog filtering, A/D converters and the computer hardware and software. The ISC system interfaces with the Suspension (SUS) Subsystem for the actuation on the optics, and with the Pre-Stabilized Laser (PSL) for actuation on the laser frequency. The modulation scheme is implemented by Input Optics (IO), according to the requirements of the ISC system.

2.2 Charge to the Review Committee

The charge to the review committee is outlined in L080020-00.

1. **With regard to requirements:**
   a) Determine whether the requirements identified in the Design Requirements Document (DRD) are complete (including functional, performance and interface requirements),
   b) advise whether proposed requirement values are appropriate,
   c) if needed, recommend additional requirements to be specified, and
   d) recommend other appropriate actions.

2. **With regard to the conceptual design:**
   a) Evaluate the conceptual design of the ISC to determine if it is consistent with the DRD,
   b) advise on whether the recycling cavity design selection is appropriate and based upon sufficiently complete information,
   c) advise whether the design is sufficiently developed to proceed with the Preliminary Design phase,
   d) advise whether the Project cost and schedule appears appropriate, and
   e) advise whether there are any significant remaining or newly-perceived risks in meeting the requirements.

3. **With regard to the preliminary design:**
   a) Advise on the preliminary design work plans, in particular the prototyping and testing plans.

The committee should develop a set of actions as a result of the review, and should follow up on the completion of the actions as part of the review process

2.3 Pre-review Comments and Questions

Some general questions which were answered by email prior to the presentation:

1. **The SPI is an important part of this design. However, there is almost no mention of it. Is this part of this review? Is there another review planned?**

The SPI will be reviewed independently. A review is planned for summer 2008.

2. **The RF readout scheme at the AS port is no longer carried as a backup. Could it still be made to work? Is the DC readout a must-work technology now?**

We won't be putting any effort into RF readout unless we find a problem with the DC readout in enhanced LIGO that makes us want to revert.

With the SRC detuning for NS-NS optimization, there was a calculated sensitivity to RF oscillator phase noise that didn't look to be viable—i.e., implied a phase noise that was hard to see how to achieve. In the broadband mode (no detuning) presumably this isn't the case, but we haven't looked; we should do this. Otherwise the OMC construction technique is compatible with making a short version to pass RF sidebands.

3. **Does the back scattering noise calculations account for a possible H1-H2 correlation? Are there any additional requirements at Hanford to reduce the correlations between H1 and H2? Should there be acoustic coupling and back scattering standards based on a stochastic result for H1-H2?**

No. No stricter scattering requirements have been set at LHO to account for possible H1-H2 correlations. We don't see a clear way to do this.

We'll also note that for advanced LIGO, the stochastic background sensitivity for LHO-LLO correlation is nearly as good as for H1-H2, since the low-frequency sensitivity is so much better. So there won't be nearly the same motivation to get an H1-H2 correlation measurement that is free from instrumentals.

4. **Fringe-wrapping seems to have been left out in the computation of the back scattering requirements. Experience in initial LIGO indicates this could be a problem. Are further calculations planned?**

We really don't expect path fluctuations close to a wavelength for the ISC detection paths. If this turns out to be completely wrong, the tip-tilt mirrors do have piston capability which we could use to stabilize the path lengths.

5. **Somewhere the IMC loop unity gain frequency is mentioned to be around 377 kHz? The CM is around 65 kHz? Is this a typo? Seems this would drive the PSL requirement for the FSS. Has anyone investigated stability through the free-spectral-range? Also, is the requirement achievable at 10 Hz?**

Not a typo, but the unity gain frequencies don't have to be this high. Initial LIGO values are good enough. The frequency noise estimate will be updated with this.

6. **The length sensing matrix is quoted for frequencies at 1 kHz. However, the sensing noise table gives values at 100 Hz. Is this a typo?**

Not a type. The noise numbers are given at 100 Hz since they tend to be more important at the low frequency end.

7. **In order to counteract the angular optical spring a unity gain frequency of 10 Hz is proposed. This seems in direct violation of the previous paragraph which states no more than a gain of 0.1 can be tolerated at 10 Hz. What is the conclusion here?**

The conclusion is that if we do need a WFS unity gain frequency of 10 Hz, we won't be able to get the WFS DARM noise contribution down to 10^{-19} m/√Hz at 10 Hz. WFS noise might dominate the spectrum up to about 20 Hz in this case. Hopefully we'll find we don't need such a high unity gain frequency.

A couple of possibilities: we could find that the local damping (suspension sensors and/or optical levers) can be set up to stabilize the system (in a low noise way); a resonant gain filter in the WFS feedback could work, in a way that produces less gain at f > 10 Hz.

8. **Does the callout of potential resonances in Table 3 of the conceptual design assume anything about how well the radii of curvature are controlled by the accuracy with which the test masses are manufactured or how well TCS controlled the radii of curvature?**

These are just calculated using the nominal g-parameter of the arm cavity (taken to be identical in each arm).

9. **The Laser Amplitude requirement in Figure 2 of the conceptual design is below the requirement described in the Advanced LIGO Pre-Stabilized Laser Conceptual Design Document. Has this information been communicated to the PSL group?**

Yes.

10. **Do we need fast shutters to protect the in-vacuum diodes? Has this question been addressed? In initial LIGO slightly damaged photodetectors can lead to increased coupling due to non-uniformity.**

The tip-tilt stages can be used as fast shutters (beam deflector-style). However we have also begun to look into other types that would insert something into the beam, like we do now.

11. **Should there be an explicit environmental coupling standard for ISC electronics and/or standards for allowable acoustic, magnetic, and RF levels in the ISC racks? In S5 we were close to being limited by coupling of magnetic fields inside the racks to ISC electronics.**

Adopting explicit standards of any type requires the ability to set quantitative limits, and to have a relatively accessible way of measuring performance. Experience to date has shown this is not often practical at LIGO.

Another approach is to require manufacturing and design standards that through careful packaging, and sensible design, provide solutions that have a historical precedent for reasonableness. This is tantamount to saying good engineering practice.

Given our experience base, it seems more fruitful to use good engineering practice and fix exceptions, than to invest in infrastructure to measure near field radiation in every conceivable geometry relative to an agreed upon limit.

12. Have there been any thoughts about the heat load of dumped beams? Will heat from beam dumps on in-vacuum optical tables (e.g. transmitted port) cause alignment problems?

Not much thought yet, but this will have to be taken into consideration when they're designed.

13. Does the computation of the oscillator phase noise include terms after the split between modulation and demodulation? Does this calculation include a difference in delay between the two paths? What about the delay through the IMC?

Currently the calculation does NOT include noise introduced after the EOM/LO split and that should be added. It also does NOT take into account any cabling delay, but it DOES include the IMC, which dominates the path difference.

There is another worry: They optical model only includes the fundamental spatial mode. The initial LIGO phase noise coupling was actually dominated by higher order spatial SB modes in the RC. The hope is that the stable recycling cavities will reduce this effect, but at this point we don't know how to calculate it.

For these reasons the phase noise requirement is specified to be smaller (quieter) than these calculations predict.

14. Is there a photodetector for laser power detection foreseen in vacuum after the IMC?

Yes, this is part of the PSL.

15. Do we have an estimate of the alignment sensing noise for the OMC? Do we have an estimate of the coupling via angle-to-length coupling in conjunction with back-scattered light to GW strain output?

First part will be answered later. Regarding the second question, the answer is no. If we understand correctly, the question pertains to angle-to-length coupling in the tip-tilt stages, making a path length modulation for back- scattered light. Just as we do now for the initial LIGO LOS/SOS, we should be able to minimize the tip-tilt angle-to-length coupling by tuning the drive channel gains, if necessary.

16. Are the proposed (3f) signals for acquisition consistent with alignment requirements for the acquisition phase? This frequency seems too high for quadrant detectors.

We don't propose using 3f signals for alignment sensing. We don't anticipate needing any global alignment feedback during the acquisition phase, given the much lower seismic noise compared to initial LIGO.

17. Are the distances given in table 2 in-vacuum, or do they include the refractive index of the passed-through optics?

These are optical path lengths. Note that the last two columns of this table should be switched.

18. How does the thermal noise affect the transmissivity of the SRM?

The SRM transmissivity is tuned to optimize the overall sensitivity, which over a broad band is limited by mirror thermal noise. This implies that we don't get any benefit from a narrow-band SRC, but are pushed to a low SRC finesse instead. This leads to the relatively high number for the SRM transmissivity (around 20%).

19. Oscillator amplitude noise seems to dominate the 10 Hz – 20 Hz region in mode 2. Does this include a stabilization circuit for the modulator? If so, at what level does it matter?

No, as stated on page 13 this uses the Wenzel crystal oscillator spec of $10^{-7}/\sqrt{Hz}$ at 10 Hz, falling as 1/f to 100 Hz.

20. Mode matching between the input mode and the common arm cavity eigenmode is at least 95% without engaging the thermal compensation system. Is this the requirement that sets the manufacturing tolerances on the mirror radii of curvatures?

Not really. These tolerances will be set by IO and COC, and the combination of manufacturing plus metrology will correspond to better than 95% matching.

21. The video cameras that image the test mass faces can also be used to monitor beam position. Is there a plan for image processing for each mirror?

Yes, exactly what is to be determined. Some testing is getting started on this at the 40M.

22. For operation at 125 W the power in REFL and POP require additional attenuation or parallel photo receivers. If additional variable attenuation is required, how will this be done?

In this case, we probably insert a mirror into the path, to direct most of the light to an in-vacuum dump.

23. What is the range of possible Schnupp settings given the hardware restrictions?

Approximately: 0 cm to 70 cm.

24. The units for oscillator amplitude noise are given in rad/√Hz at some places. Is this a typo?

It's meant to be the same as dBc/Hz.

25. Is there any chance that radiated magnetic fields from the tip- tilt mirrors are going to cause noise problems via EM coupling, or through interaction with nearby (or not so nearby but very sensitive) other suspensions?

The suspension closest to a tip-tilt mirror will probably be the OMC suspension. Even then the tip-tilt actuators will be ~ 0.5 m from the OMC suspension magnets. This doesn't sound like much of a danger to us, but we will keep our eye out for any such trouble in the enhanced LIGO setup.

26. Can in-vacuum flipper- mounts really work? Or, do they cause too much disturbance?

Currently we don't expect to use in-vacuum flipper mounts (the ones shown in Fig 29 are not in-vacuum), but if we do, we'll have to look at this.

27. At what level are the OMC dither modulations expected to show in the DARM spectrum? Can the frequencies be changed for a particular pulsar search? Is there a way to estimate other non-linear processes which will cause cross products within the dither system, or in connection with other modulation sources? Will the baseband seismic noise be modulated up to GW frequencies via this dither?

We assume this refers to the tip-tilt alignment dithers (OMC length dither is above-band). Of course it depends on how hard we dither, which depends on the bandwidth we need for OMC alignment control, which depends on input fluctuations and how they really couple. We don't have good estimates for all of these. We'll learn from the enhanced LIGO OMC how these factors play out, and be able to make some extrapolations to advanced LIGO.

28. Are there any plans to make the common mode loop digital?

Not currently. It could be useful if the hardware gets better, but not necessary.

29. In-vacuum beam dumps: K. Arai researched possibly better beam dumps using three planes of absorbers instead of two. Has anyone looked into this? What is the isolation of the beam dump? How much light scatters back into the interferometer?

We will look into these, haven't yet.

30. Is there a plan to investigate environmental noise sources (other than magnetic fields acting on the penultimate mass magnets), for example, acoustic coupling for non-vacuum parts of the system?

No plans for anything further—any suggestions?

31. Could there be a problem from emitted RF coupling to the RF parts, or, externally generated RF fields coupling to the RF system? We have seen commercial ALE signals at LLO get to a level at 25 MHz that, according to PEM injections, would produce noise at 1/10 of the DARM noise floor.

Echoing our response to #11, our approach is to use good engineering practices, here with regards to RF shielding.

32. Section 2.2.5: The last sentence of this section starts; "On the other hand". What is meant here? "On the other hand" implies that 90º corresponds to an intensity on the DARM PD of more than 100 mW. Clarify what is meant with the numbers 100 mW, 10 pm and 90º. What do 100º and 90º correspond to and is this going to be an issue (or is this just a matter of attenuating?).

Here's a rewrite of the whole paragraph (2.2.5):

Loss difference in the arms and any asymmetry in the BS results in some light on the AS_DC photo diode even when the DARM offset is zero. Assuming a differential arm round trip loss of 30 ppm this light is on the order of P_0 = 1 mW (4 mW for 60 ppm, see figure 6).

The AS_DC light due to DARM offset is quadratic in DARM offset and reaches P_DARM = 100 mW at a DARM offset of ~ 12 pm (figure 6). 100 mW is also hat we think our DC photo diode should be able to handle.

The homodyne phase is defined as the *arctan* (P_DARM / P_0). Theoretically the NS/NS range peaks at a homodyne phase somewhere around 100º, but the sensitivity gain compared to a homodyne phase of 90º is minimal. Also technical noise couplings such as Intensity noise become bigger for small DARM offsets, thus driving us to larger offsets (i.e. closer to 90º homodyne phase). Thus we most likely will operate at a DARM offset of about 10 pm.

33. Section 4.6.1 (page 28): The recycling cavity assumes a π/2 difference in Gouy phases. In the recycling cavities this means that any 01 or 10 mode is dark but any 02 or 20 mode will be bright (or close to bright) with power in these terms depending on the recycling cavity mode mismatches. Will these cause any problems?

We don't see any problems as long as the modes are not resonant. The 20 mode being bright refers to the Michelson interferometer formed between the two recycling cavities. It does not mean that the mode is resonantly enhanced in any cavity. We are currently fine tuning the Gouy phases to ensure that none of the low order modes is resonant in any of the combined cavities; the current set of numbers is already very close.

34. The back scatter analysis is done for all longitudinal DOFs. Not for angular. How does scatter affect the differential wavefront sensing loops?

In principle scattered light could contaminate these sensors. But since the longitudinal sensors get the bulk of the light, if we control scattering for them, the WFS should be ok.

35. How large are the RF offsets for detuned SRCL? How large are the signals in the orthogonal phase? Will this pose a problem to get to low sensitivity?

For SRCL: Refer to figure 7: The green trace shows the RF error signal from double demodulation as function of SRC detuning angle. Thus for 20º of detuning the locking- offset is about 3 mW. The orthogonal phase is roughly the same size.

This is roughly the same amount of RF we observed in initial LIGO. Note though that all these calculations only use the fundamental spatial mode. So they ignore effects from higher order spatial modes, e.g. misalignments, which would come on top of this.

36. Do the ASC signals include sideband on sideband effects? Are they significant? How much do they change as function of the thermal lensing?

The ASC signals were not modeled using higher order sidebands. However, we calculated the signals higher order sidebands generate at the various ports. Their amplitudes are in general well below the amplitudes of the first order signals: for input and end test masses ~ 5 orders of magnitude and for recycling mirrors ~ 2 - 3 orders of magnitude. We did see some changes (not an increase, a re-distribution) in the coupling between the differential test mass degrees-of-freedom and the signal recycling degree-of-freedom in the SR channel. It doesn't appear to cause any additional problems but this would need some further investigation. Based on this, we don't believe that the higher order sidebands create any problem. However, we will have to include them in future simulations.

37. Do the alignment fluctuations of the beam reduction telescope mirrors pose a special problem? Are the aligned and damped by optical levers?

We think they won't. Their fluctuations are small compared to the beam divergence (thanks to the seismic isolation). There will be optical levers on them.

38. For the preamp UHV cans: do we plan to have a canning machine at the site? Is it clear this is a better solution than develop in vacuum circuitry? What is the trade-off?

There is no plan to invest in a "canning machine" at the site. There will be spares available for the in-vacuum designs, so simple replacement of a damaged device is immediate. For damaged items needing repair, or to modify an existing design, an electronics pod can be opened, or sealed again, by the manufacturer on an overnight basis. Compared with the time to formulate a plan for intelligently changing a design, and opening the vacuum system, a few days of turnaround time seems reasonable.

Development of exposed, in-vacuum circuitry is R&D. A trade-off study comparing a hypothetical solution with an existing solution is the basis for an R&D proposal. Given our available resources, we would first have to agree that a second solution to an already solved and relatively low tech problem is needed.

39. How stable do the loop gains need to be? Do they have to remain constant to a fraction of a percent including the suspension and/or seismic actuators? Does this lead to a need for constancy or constant calibration in the electromechanical constants? This should be checked against what SEI and SUS expect to deliver, and may place new requirements on those subsystems.

We're not counting on them being any more stable than in initial LIGO, so we don't think any new demands need to be put on the actuators.

2.4 Conceptual Review Presentation

For the following topics the review committee felt strong enough that we asked the ISC team to address them during the presentation.

2.4.1 Optickle Simulation Program

Committee request: *"A. We would like to have a (very) short introduction to Optickle: in particular, the modeling approach, the assumptions that went into it, what kind of physics is included and how it was tested. What about radiation pressure effects? Optical springs, etc?"*

The presentation is given in G080255-00, pages 2 to 13. We feel that the tools for modeling the ISC system are in reasonable good shape.

Recommendation: We encourage the ISC team to continue improving documentation of the algorithms as well as establishing a set of careful validation tests.

2.4.2 Modes of Operations

Committee request: *"B. There seems to be a lot of modes of operations. Most of them are not worked out in detail, but it seems unrealistic that so many will be needed. We would like to hear some additional information.*

One might argue that the scientific justification for some of these modes is marginal. Improvement are usually only of the order of 30% in sensitivity, but degradation in other frequency bands is significant. In particular, there seems to be little reason to invest in detuned modes at this time.

Is mode 0 a stepping stone before including a SRM? How much of future ISC time will be used for developing some of these modes? Is it possible to go forward and concentrate on a single mode of operation?"

The presentation is given in G080255-00, pages 14 and 15. The committee agrees that only operating mode 1b (non-detuned broadband resonant sideband extraction) should be carried forward in the preliminary design.

Recommendation: Other modes of operating a dual recycled interferometer should be considered future options, but not made impossible.

There was no compelling reason given why operating mode 0 (the initial LIGO configuration) should be serving as a stepping stone for commissioning. It is not clear if this would actually save overall commissioning time or if this would require solving the wrong problems. It is not clear what the implications on configuration, controls and schedule are. In addition, the criterion for acceptance of an interferometer is that all length degrees-of-freedom be under control and the signal recycling cavity is one of those degrees-of-freedom.

Recommendation: We recommend that a trade-study be undertaken to investigate the advantages and disadvantages of a "stepping stone" approach.

2.4.3 Availability Goals

Committee request: *"C. The requirement lists availability goals, but nowhere are they worked into the conceptual design. How do these requirements drive the design? What steps will be taken to ensure that they can be met? What kinds of lessons have been learned with initial LIGO and how do they affect the current design? What steps are taken to address maintainability?"*

The presentation is given in G080255-00, page 16. We expect the ISC team to follow good engineering practices, but are wondering what they are. For example, what will be done to assure that the in-vacuum equipment performs as required?

Recommendation: We recommend that these engineering practices be written down.

2.4.4 Interface with the Seismic System

Committee request: *"D. What exactly is the interface with SEI? How certain are we that the provided performance numbers will be met? Especially at very low frequencies? Are we talking about average or worst cases? How are we doing in the 5-10% percentile?*

Is there enough force to deal with radiation pressure---both longitudinal and due to the Sidles-Sigg angular instability? In particular during times of heightened seismic activity which presumably *leads to larger than usual power and angle fluctuations? What is the headroom to deal with non-stationary environmental disturbances?"*

The presentation is given in G080255-00, pages 17 to 22. The interface to the seismic system consists of a slow feedback path which can be applied if useful. The performance modeling uses an elevated seismic spectrum. However, the HAM ISI system has not yet been included.

There seems to be enough force to control the interferometer once it is locked. However, additional modeling could help answering the question what the maximum seismic "jolt" is the system can handle.

Recommendation: Collect all information where the ISC is depending on the BSC seismic system and ensure that both the interferometer sensing and control team and the seismic isolation team believe that the requirements and interfaces can be realized.

2.4.5 Technical and Schedule Risk

Committee request: *"E. We would like to see a list of the highest risk items---both technical and schedule. What steps are taken to address these risks? On what time scale will they be retired? What is the contingency if we fail to meet them? Are there viable alternatives? Two items in particular: the DC readout scheme and power handling."*

The presentation can be found in G080255-00, page 23.

1. DC readout

The design is committed to a DC readout scheme for the gravitational wave readout. An RF scheme might still be possible for the non-detuned configurations. For detuned configurations an unrealistically low oscillator phase noise requirement has been identified in the case that RF readout is to be used. The Enhanced LIGO project will give important feedback, if a DC readout scheme is viable.

2. Power Handling

Sidles-Sigg Angular Instability: Enhanced LIGO will give important insight in handling angular instabilities. Although the enhanced LIGO am cavity power is far less than in advanced LIGO the problem will be of similar magnitude due to the cavity geometry. However, the conceptual design did not work out how an angular instability at several Hz is compatible with the noise requirements in the alignment sensing and control system.

Recommendation: Identify a possible scheme to stabilize the angular controls at full laser power without degradation of the noise performance at low frequencies. Or, if not possible, show what degradation can be expected as function of laser power.

Photodetector Light Power: About a factor of two or three more power has to be handled by the photodetectors for the longitudinal degrees-of-freedom. The factor is even higher for the alignment degrees-of-freedom.

Recommendation: Consider a test on an interferometer to validate the design.

3. Lock Acquisition

Seismic Platform Interferometer: An important step in locking the interferometer arm cavities is the seismic platform interferometer (SPI) which was not ready for review.

Recommendation: Hold an independent review during the summer of 2008.

3f-Scheme: The 3f scheme is new to LIGO and needs to be validated.

Recommendation: Use the 40M to do the testing.

4. In-vacuum Detection

In-vacuum detection benches are new to LIGO. They will be partially implemented in Enhanced LIGO. This experience will help.

2.4.6 Sensing Matrices

Committee request: *"F. There should be additional discussion about the sensing matrices and their 'problematic' elements. Do we rely on gain hierarchy? Could there be problems because some of these elements are not stable enough, say, during power up? The effects of higher order modes, sideband-on-sidebands, sideband imbalance, etc. on these."*

The presentation is given in G080255-00, pages 24 to 31. Even so at first sight neither higher order modes nor sidebands-on-sidebands seem to constitute a problem, a more detailed analysis will be required by the time of the preliminary design. The choice of a stable recycling cavity gives the advantage of stable Gouy phases and, therefore, it is expected that an imbalance of the RF sidebands is a less severe problem than in initial LIGO. One problem is the common ITM alignment signal which is currently degenerate with the power recycling mirror orientation.

Recommendation: Compute the alignment sensing matrix for the beam splitter as well as for the spatial position on the end test masses. For a complete picture the beam telescopes which are part of the power and signal recycling cavities should be included as well, so that an optimal control scheme can be devised.

Recommendation: Try to identify a better sensing scheme for the common ITM alignment signal. What is the effect of adding a non-resonant sideband?

Recommendation: Investigate the robustness of the proposed 3f signals for lock acquisition with respect to misalignments of the maximum amount given by the acquisition alignment tolerance. Investigate the robustness of the standard locking signals within the alignment tolerances for acquisition (where applicable) and detection.

2.4.7 Correction Paths

Committee request: *"G. The section 3.5 about the correction paths is rather short and maybe confusing. We like to see a discussion during the review presentation with greater reference to the plots."*

The presentation can be found in G080255-00, pages 32 to 40. This part of the design seems well understood. Currently, initial LIGO requires a cancelation in the correction paths at the 1% level. This seems adequate for advanced LIGO. VIRGO currently deploys 0.1% correction paths.

Furthermore, the Michelson degrees-of-freedom cancellation assumed a 20 Hz bandwidth controls system which is higher than required.

2.4.8 Sensing Noise Requirements

Committee request: *"H. A very similar situation exists with the sensing noise requirements section 9.4. We would like to have some clarification how things are hanging together."*

The presentation can be found in G080255-00, pages 41 to 45. This part of the design seems well understood.

2.4.9 Programming

Committee request: *"I. What kind of programming effort will be required to implement the ISC code? Who is going to write it? Test it? How are changes handled during commissioning? Are there any regression test suits planned? How much time will be needed for verification and qualification? One of the problems in initial LIGO is that there is no place to test new code except the full interferometer. Are there plans for a test setup where ISC code can be run and tested independently? Is there a need for a real-time interferometer simulator?"*

The presentation can be found in G080255-00, pages 46 and 47. The feedback compensation network which keeps the differential arm cavity length on resonance is part of the gravitational readout. Having a full understanding of the corresponding computer code is crucial in a convincing detection of gravitational waves. In initial LIGO the characterization of the length sensing and controls software is not well documented; substantial improvements are needed. We feel that this effort is not sufficiently staffed and more resources need to be allocated.

Recommendation: We understand that the current ISC team consists of very few software persons. We recommend that more resources are actively recruited from the detector characterization group.

Recommendation: A test plan and software characterization effort should be worked out for the preliminary design.

2.5 Other Observations and Recommendations

2.5.1 Safety

Recommendation: Identify the potential safety hazards associated with assembly and test, installation and commissioning. Make sure that laser beams can not escape the vacuum system in an unsafe way. Make sure that systems which steer the laser beam employ a fail-safe design.

2.5.2 Diode Damage

Slight damage to the AS diodes in initial LIGO resulted in increased coupling of beam jitter. Will this be a problem in advanced LIGO?

Recommendation: Determine what level of power is allowable on the diodes and what diode protection is required to prevent problems in advanced LIGO.

2.5.3 Wide Angle Scattering

Small angle scattering at the dark port has been investigated, but we wonder if wide angle scattering might be a problem, especially to the vibrating chamber walls and back.

Recommendation: Estimate the effect of wide angle scattering, and, if needed, develop a plan to shield the photodetectors.

2.5.4 In-Air Beam Paths

None of the out-of-vacuum beam paths are required for operating in low noise mode.

Recommendation: The ISC team should make sure that all beams leaving the vacuum system can be blocked from the inside and properly dumped.

2.5.5 Location of Input Mode Cleaner Sensors

The position of sensors of the input mode cleaner has not been fixed yet. The beams are available in HAM 1.

Recommendation: Decide if the input mode cleaner sensors need or should be located in-vacuum.

2.5.6 OMC Alignment Sensing Noise

We don't have an estimate of the alignment sensing noise for the OMC.

Recommendation: Estimate the alignment sensing noise of the OMC.

2.5.7 In-Vacuum Cameras

Is there a need to look at beam positions on photodetectors or other components which are mounted in vacuum?

Recommendation: Determine if there is a need for in-vacuum cameras.

3 Schedule and Person-power

3.1 Cost and Schedule

Not reviewed.

3.2 Person-power

The interferometer sensing and controls development significantly profits from the Enhance LIGO upgrade and the testing at the 40M. With the resources available for the Enhanced LIGO upgrade and for the 40M testing we feel that the length sensing and controls system is adequately staffed to proceed to the preliminary design.

Even so the alignment sensing and controls system also profits from the high power operations in Enhanced LIGO, this system is behind the development of the length sensing and controls system. We feel additional resources are required for the preliminary and final design.

Depending on the decision on the seismic platform interferometer additional resources might be required to develop and test this new system.

Software programming and testing is not adequately represented in the interferometer sensing and controls system. Additional resources are required to characterize computer code and perform testing. We recommend that more resources be actively recruited from the detector characterization group.