LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Proposal for a Squeezed H1 Interferometer

Daniel Sigg, Nergis Mavalvala, David McClelland, Ping Koy Lam, Roman Schnabel,
Henning Vahlbruch and Stan Whitcomb

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LIGO Science Collaboration

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California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. 159
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1 Proposal Summary

We propose to inject squeezed light into the Hanford 4 km interferometer to improve its sensitivity by 3 dB in the frequency band dominated by shot noise. At the Hanford Observatory there are about six months between the end of the 6th science run and the beginning of installation for advanced LIGO. We propose to use this time frame to install a squeezed light source and validate the concept of gravitational wave detection below the standard quantum limit.

Advanced LIGO demands very high power levels in the long Michelson arms. Close to a mega Watt of laser light has to be stored in the arm cavities in order to reach the sensitivity goal. This will be challenging. Optical waveform distortion due to absorption and the excitation of parasitic instabilities both have the risk to limit the maximum arm cavity power. Using non-classical light states have the potential to achieve similar performance with less power. We see this proposal as an important step to mitigate the technical risk associated with high power operations in advanced LIGO.

The technology to generate squeezed vacuum states has progressed quickly over the past few years. A suitable light source which generates squeezing down to 10 Hz has recently been demonstrated. Interferometric detectors have been squeezed before—however, no experiment was performed at frequencies or sensitivities directly relevant for future detectors.

2 Project Description

2.1 Context and Overview

The current thinking of quantum noise propagation in interferometers stresses the importance of the ‘open’ port of the beam splitter. It is thought that vacuum fluctuations enter the experiment there and interfere with the local oscillator field to produce the noise observed at the detection port. For an interferometer using the Schnupp modulation scheme the light entering the anti-symmetric port has to be squeezed both at DC and at twice the modulation frequency. For the LIGO interferometers the reflectivity of the Michelson interferometer is about 50% for light entering the anti-symmetric port at twice the modulation frequency. This means that the light at the input port at twice the modulation frequency needs to be squeezed as well.

In contrast, an interferometer which uses a DC offset to sense the differential arm motion only needs to squeeze the DC light entering the anti-symmetric port. Due to the technical difficulties to inject squeezed light at twice the modulation frequency into the input port we will only consider measurements at an interferometer which deploys a DC readout scheme. For us this means the 4 km interferometer at Hanford.

The benefits of non-classical methods for improving the sensitivity of a gravitational wave detector have been worked out in great detail. Particularly interesting to us is the fact that it allows for lower light levels in the interferometer at similar sensitivity levels. Advanced LIGO requires a 200 W laser and boosts the arm cavity power near a mega Watt to achieve its baseline design sensitivity. Optical absorption in the substrate of the input test mass introduces an optical lens, both because of a physical deformation and because of the temperature dependency of the refractive index. In initial LIGO which has arm powers around 15 kW a thermal compensation system was developed to counter this effect. In advanced LIGO special compensation plates will be placed in the Michelson arms, so that the thermal compensation system can be implemented without interfering with the input test masses. Due to the much higher arm powers using a material with extremely low absorption and scattering is paramount. This is still an area of active research and development. Ultimately, this will set an upper limit on the arm powers.

Another problem of running high light levels in a cavity is the possibility to excite a body mode of a test mass and introduce a parametric instability. This requires an optical higher order mode shifted by the frequency of the test mass body mode to be resonant in the cavity. It also requires the motion of the body resonance to have a non-zero overlap with the TEM00 optical mode. However, calculations have shown numerous possibilities for almost any cavity geometry. Again, there is an active field of investigation to find ways to mitigate this effect.

Finally, high light levels also introduce an angular instability. This instability will be suppressed by an active alignment feedback compensation network. However, this will become increasingly difficult at higher power levels.

Considering the risks involved with high power operations it seems prudent to have available an alternate means to achieve similar performance. Squeezing has been demonstrated on interferometers, but not at the sensitivity levels and at the frequencies relevant for advanced LIGO. We believe that testing a non-classical light source at the 4 km interferometer at Hanford is the best way to demonstrate and validate squeezing technology for use in gravitational wave detectors.

2.2 Current Status of Technology

Recent progress in the development of a squeezed light source has eliminated the seed field at DC[1]. This together with a carefully attention to scattered light paths has yielded a squeezer with good performance down to a few Hz[2]. A non-classical noise suppression of up to 6.5 dB below vacuum noise has been achieved.

GEO600 will test squeezed light input in the 2008/2009 time frame and solve remaining yet unknown problems. The goal is a stable long term improvement of 3 dB or better down to 500 Hz with tuned signal-recycling and maybe with an output mode cleaner.

This allows the H1 test to focus on noise and sensitivity issues that can only be done on the LIGO interferometers and at a sensitivity level directly applicable in advanced LIGO. Having the GEO600 effort preceding the H1 experiment significantly strengthens the outlook. An auto-alignment system which will ultimately be needed for long term operations can easily be commissioned there.

2.3 Outlook

The 5th science run of LIGO with one year of triple coincidence data at design sensitivity has been finished on September 30th, 2007. An enhancement project is currently underway. Its goal is to implement a dc readout scheme with an in-vacuum output mode cleaner at both LIGO 4 km

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[1] S. Chelkowski, H. Vahlbruch, K. Danzmann and R. Schnabel, *"Coherent control of broadband vacuum squeezing,"* Phys. Rev. A 75, 043814 (2007).

[2] H. Vahlbruch, S. Chelkowski, K. Danzmann and R. Schnabel, *"Quantum engineering of squeezed state for quantum communication and metrology,"* New J. Phys. 9 (2007) 371.

interferometers and increase the sensitivity to a standard inspiral source by a factor of two. It will also implement a 30 W laser and better performance input optics which can tolerate higher power. This together will improve the shot noise sensitivity at high frequencies up to a factor of four. The current plan calls for another 2 year long run with enhanced sensitivity. This will lead directly into the start of the advanced LIGO installation in 2011. However, the start of installation is staggered between Hanford and Livingston by about six months—with Livingston going first. This leaves a window of opportunity at Hanford to set up a squeezer experiment.

In Figure 1 the green curve shows the projected sensitivity of enhanced LIGO, whereas the red curve shows the expected improvements when 3 dB of squeezing is applied.

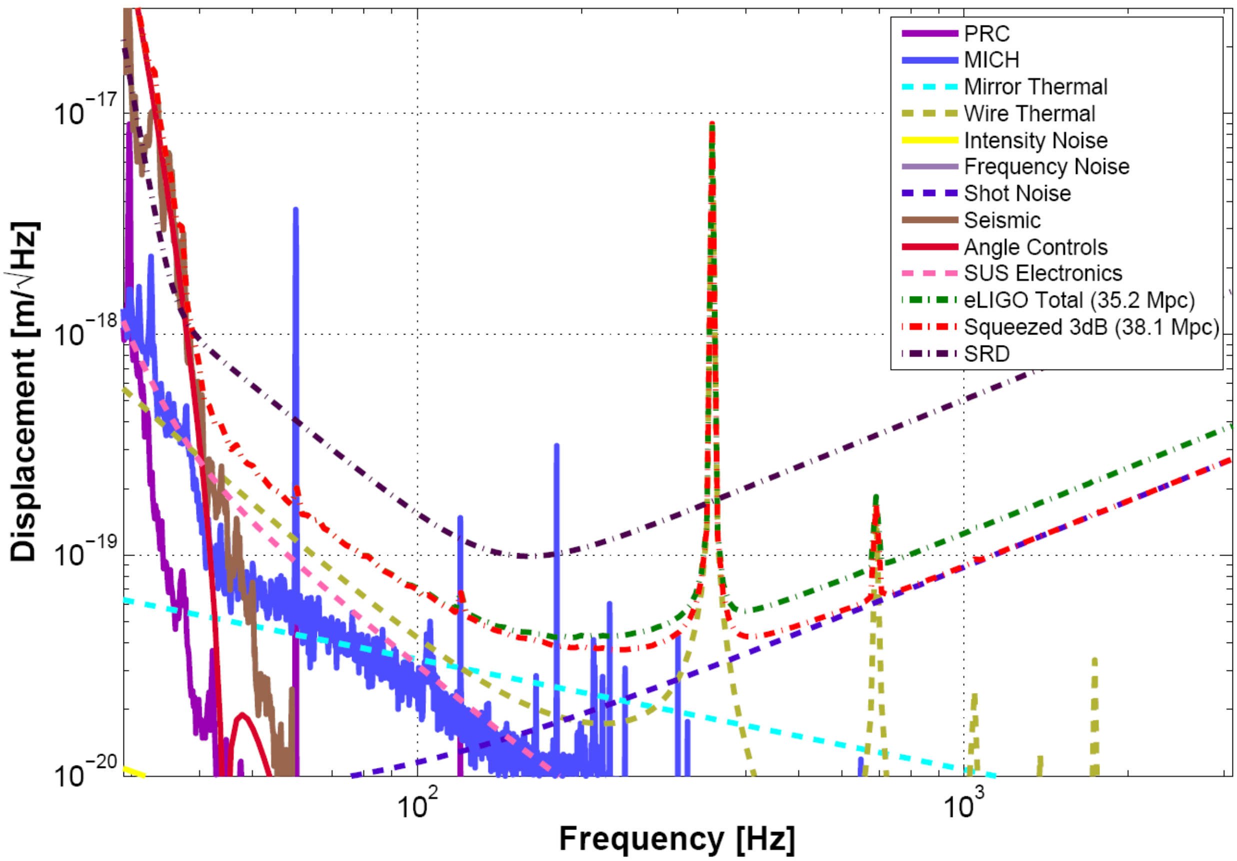

Figure 1. Projected improvements of a squeezed interferometer after Enhanced LIGO has been implemented. See text for a description of the individual curves.

The Enhanced LIGO sensitivity curve is shot noise limited above about 250 Hz. The curves labeled PRC and MICH are noise contributions from the auxiliary degrees-of-freedom, whereas Mirror Thermal and Wire Thermal denote the thermal noise contributions from the test masses and the suspension wires, respectively. Because of the DC readout scheme the laser intensity and the laser frequency noise make only very small contributions. Additional noise terms arise from ground motions due to man-made and seismic activities, from the angular controls system and from the suspension electronics. To produce the projected noise curve of the squeezed interferometer the shot noise was simply scaled down by 3 dB, whereas all other terms have been kept the same.

3 Experiment

A schematic view of the experiment is shown in Figure 2.

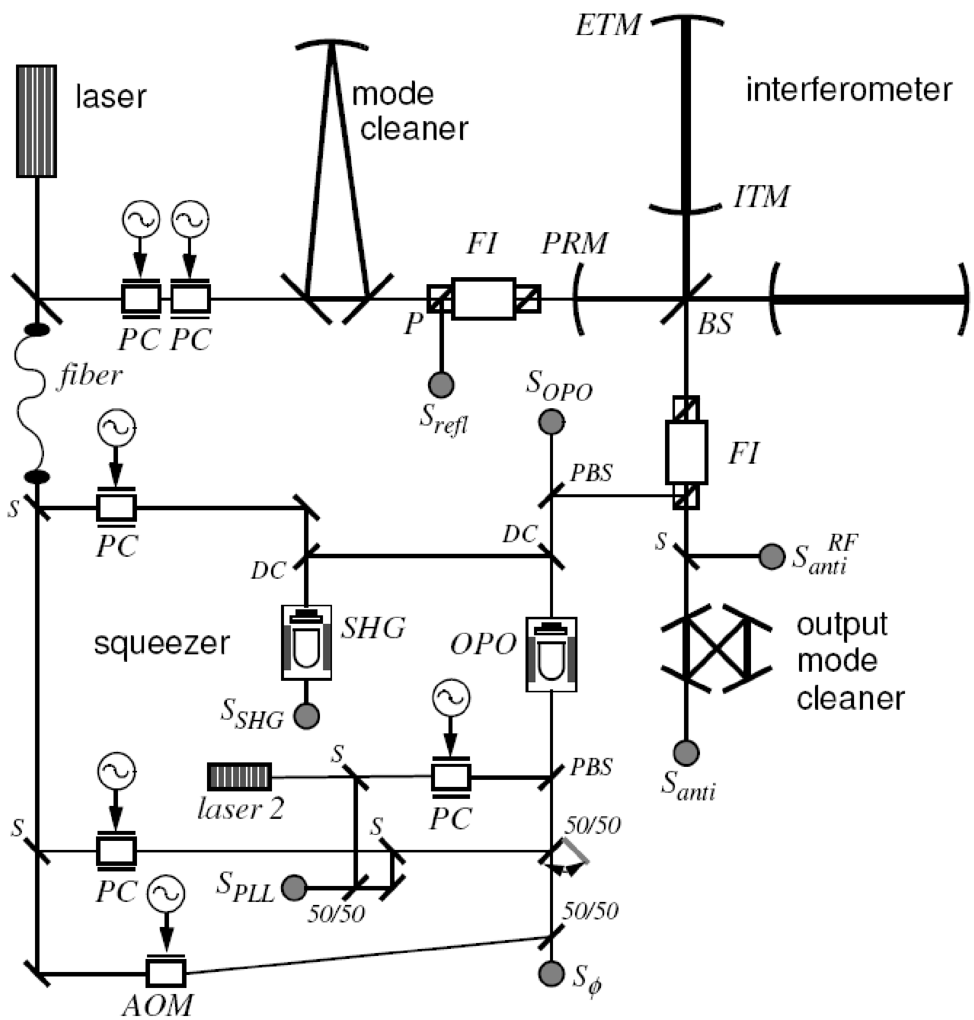

Figure 2. Schematic view of the experiment. Part of the main laser light is launched into a fiber and brought to the squeezer. A sample beam (S) is fed into the second harmonic generator (SHG). The doubled output is then sent to the optical parametric oscillator (OPO) by use of dichroic mirrors (DC). Laser 2 runs in the opposite polarization and it is locked to the main laser through S_{PLL}. It gets injected into the OPO through a polarizing beamsplitter (PBS). The corresponding transmitted beam is separated from the squeezed beam by another PBS. Then, signal S_{OPO} is used to lock the OPO. The OPO can also be locked with the main laser light by a flipper mirror. This is used for alignment. The squeezer phase is locked by a frequency shifted subcarrier which is produced by an AOM. This beam is sensed by S_ϕ in reflection of the OPO. The transmitted subcarrier is launched into the interferometer together with the squeezed vacuum state. The phase between the squeezed field and the local oscillator is sensed by demodulating the signal S_{anti}^{RF} with the subcarrier frequency. Pockels cells (PC) are used to impose RF sidebands which are used for Pound-Drever-Hall locking.

3.1 Baseline Design

A squeezed light source requires a seed from the main laser beam. This beam has to be split off at the input of the interferometer and brought to the anti-symmetric port through a fiber. The squeezer will be installed near the anti-symmetric port. We propose to use the same type of squeezer as has been demonstrated by the Hannover group. The squeezer will be pre-assembled on its own breadboard, so that it can be installed in the experiment in a short time. The location of the squeezer is in the acoustic enclosure near the anti-symmetric port.

The LIGO interferometers have a Faraday isolator placed between the anti-symmetric port and the detection bench. This Faraday isolator prevents back-scattered light from entering the interferometer. This means that we have to inject the squeezed beam through an auxiliary port of the second polarizer of this Faraday isolator.

Assuming we achieve 6 dB of squeezing at the injection point to the anti-symmetric port and assuming that the additional losses through the Faraday, the interferometer, and the output mode cleaner are not larger than 30%, we should be able to obtain 3 dB of squeezing at the interferometer output.

3.2 Low Frequency Squeezer

The main feature of the low frequency squeezer developed by the Hannover group is that there is no seed beam from the main laser in the optical parametric oscillator. Instead, its cavity is locked by a frequency shifted second laser which operates in the opposite polarization. The frequency shift is of order a GHz and has to account for the birefringence of the non-linear crystal in the optical parametric oscillator. The laser light from the main laser is doubled by a second harmonic generator. It is then fed to the optical parametric oscillator where it serves as the pump beam for amplifying the vacuum and squeezing it. The phase of the pump beam is phase adjusted to the main laser light by using a frequency shifted probe beam which is locked to the optical parametric oscillator. Special attention has to be put on beam dumps, acoustic damping, temperature stability and air currents to prevent stray beams from deteriorating the squeezing at low frequencies. The Hannover experiment showed 6 dB or more of squeezing down to about 5 Hz. A similar setup will be sufficient for this experiment.

Our baseline design launches the beam for the squeezer through a fiber. Because of the limitations of fibers this arrangement has to be tested beforehand. As an alternative one could guide the beam within the vacuum system to the anti-symmetric port by use of steering mirrors. However, we strongly suspect this won't be necessary.

Another strong possibility is to use an additional laser to pump the second harmonic generator and lock it to the fiber beam. This would allow for greater flexibility and a filtered carrier field from the interferometer signal port takes over providing the best phase reference possible.

3.3 In-vacuum Modifications

Injecting a squeezed light source into the anti-symmetric port of the 4 km Hanford instrument requires a change of the in-vacuum Faraday isolator. This Faraday isolator currently prevents beams scattered away from the detection bench to enter back into the interferometer. It also requires the squeezed beam to enter the interferometer through the rejection port of the second Faraday polarizer. Unfortunately, the currently installed isolator has none of the additional Faraday ports available. It will have to be replaced. A couple of additional 2" mirrors will also be required to steer the squeezed beam into the Faraday isolator.

Initial alignment of the squeezer should be straight forward. A beam entering the squeezer port of the Faraday will be reflected by the short Michelson and sent back to the anti-symmetric port. The beam is aligned, it if has the same shape and direction as the normal interferometer beam at the anti-symmetric port. A fine alignment can be done when the system is back under vacuum using the same technique. By utilizing phase cameras or wavefront sensors and by comparing the spatial profile of the interferometer TEM00 mode with the frequency shifted probe beam—which is injected together with the squeezer beam—one should be able monitor the alignment in-situ.

3.4 Preparation and Testing

While the 6th science run is taking data and leading up to the squeezer experiment, the actual squeezer has to be built on a breadboard in the optics lab at Hanford. All relevant performance parameters have to be measured, reviewed and qualified. This includes the fiber for the squeezer beam as well as the injection through the auxiliary port of the Faraday isolator. At the same time a new Faraday isolator has to be assembled and tested, so it can replace the current in-vacuum one at the earliest possible time after the science run has finished.

We also plan to develop a model which includes performance projections and a noise budget. Part of this model will be working out the requirements on mode matching, alignment and any other parameters we have to control for optimal operations. This model can hopefully be extrapolated to Advanced LIGO in a straight forward manner.

3.5 Installation and Measurements

Installing the Faraday isolator at the anti-symmetric port will be the first task after the science run ends. During the pump-down wait the squeezer will be carried to its location at the anti-symmetric port. Next, the fiber will be installed so that the squeezer can be characterized in its final configuration.

It is important that the squeezed vacuum beam is well aligned and mode-matched to the interferometer beam. Any mismatch in overlap will look like a loss and will reduce the squeezing potential. For this experiment we do not envision an auto-alignment system. The beam will have to be aligned by hand. This will probably limit the duration of operations, but should be sufficient for demonstrating the improved sensitivity.

There will be about four to five months to perform and tweak the squeezer beam into the interferometer, to establish a new noise floor and to characterize the performance as part of the gravitational wave readout. The experiment is deemed a success, if improvements in sensitivity of 3 dB can be demonstrated for frequencies above about 200 Hz.

4 Cost and Schedule

4.1 Schedule

The proposed schedule is shown in Table 1. There are about three years available for preparations before the end of the science run. A vacuum vent will be required after the science run. The pump-down wait will be between four and six weeks. This will leave about four to five months for the actual experiment.

Table 1: Propose schedule

	Task	Description	Dates
1	Squeezer Prep	Build and characterize squeezed light source on a bread board in optics lab	2008 – EoS6[3]
2	Faraday Prep	Build new Faraday	2010
3	Modeling	Model squeezer performance and develop noise budget	2008 – 2012
4	Vent	Install in-vacuum Faraday and steering optics	1/1 – 1/2[4]
5	Squeezer installation	Install squeezer at final location and install fiber for squeezer beam	1/3 – 1/30
6	Measurements	Measure interferometer performance with squeezer installed, refine noise budget	2/1 – 5/30
7	Report	Remove squeezer, finish modeling and prepare report	6/1 – 11/30

4.2 Decision Points

There are two main phases to the project: The preparation work which consists of building the squeezed light source and the actual installation and measurement phase. A decision to start the preparation will have to be made by mid 2008 to allow for money to be allocated in fiscal year 2009 and work to be started in the same year. A second decision point is located halfway into the sixth science run before the work on the Faraday starts. At this time it should be clear if the commitment to go ahead is compatible with the advanced LIGO progress.

[3] End of the sixth science run of LIGO.

[4] These dates are relative to the end of the science run

4.3 Cost Estimate

This cost estimate is very rudimentary and should be considered preliminary. Costs savings can be realized by recruiting support from other LSC institutions and by sharing or reusing existing equipment.

A cost estimate is presented in Table 2. The main equipment costs are associated with buying the components for the squeezer. We may need to buy a new Faraday isolator as well, unless we can use an Advanced LIGO prototype one. We also ask for support for one postdoc as well as one graduate student to perform this experiment.

Table 2: Cost estimate.

	Item	**Estimated Cost (k$)**
1	Support for one postdoc (3 year, 50%)	60/y
2	Support for one graduate student	60/y
3	Faraday isolator assembly	25
4	Fiber launch system	7
5	Auxiliary laser	35
6	Squeezer setup (optical)	100
7	Dual wave-length laser[5]	100
8	Electronics	30
9	Mechanical engineering	30

[5] This is as a contingency, in case we find that to be more reliable than fiber porting many watts of 1064 nm to a homemade SHG.