LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Proposal for a Squeezed H1 Interferometer

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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 6^{th} 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 circulating in the long arms. Close to a megawatt 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

Current ideas about quantum noise propagation in interferometers stress 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 of injecting squeezed light at twice the modulation frequency into the input port, we will only consider measurements on an interferometer which deploys a DC readout scheme. A natural candidate is the 4 km interferometer at Hanford.

Squeezed state injection is useful for improving the sensitivity of an operational interferometer, but it can it also serve as a risk management tool in interferometers with high circulating power. Injection of non-classical states of light is not only promising for reducing quantum optical noise in gravitational wave detectors, it also allows for lower light levels in the interferometer at similar sensitivity levels (see Figure 1).

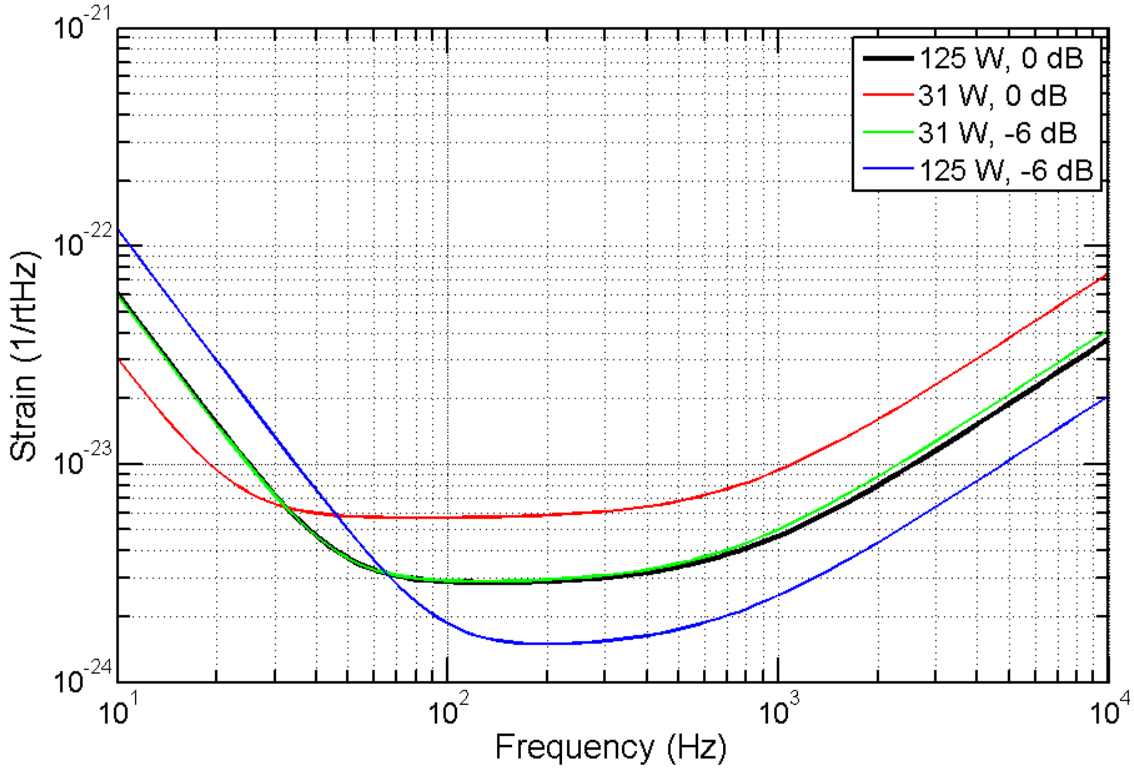

Figure 1 Quantum noise in Advanced LIGO. The black curve shows the quantum noise limited sensitivity for the Advanced LIGO baseline, with 125 W of laser power at the interferometer input, and no signal cavity detuning. The red curve shows the sensitivity if only 30 W could be used; the green curve shows recovery of the baseline sensitivity if 6 dB of squeezing were injected into the interferometer with 30 W of input power; and the blue curve corresponds to 6 dB of squeeze injection and 125 W of input power.

Advanced LIGO requires a 200 W laser and boosts the arm cavity power near a megawatt 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

In recent experiments the performance of continuous wave squeezed light sources at 1064 nm has been significantly improved[1]. The DC control field of a squeezed light source was replaced by a RF control field shifted by several MHz[2]. This together with a careful attention to scattered light paths has yielded a squeezer with good performance down to a few Hz[3]. A non-classical noise suppression of up to 6.5 dB below standard shot noise has been observed in the frequency region between 10 Hz and 10 kHz. All degrees-of-freedom of the squeezed light source with respect to a DC local oscillator beam were coherently controlled.

A squeezed light source will be one of the major upgrades for GEO600/GEO-HF. Injecting squeezed light into GEO will be implemented in 2009 and remaining yet unknown problems be solved in the same year. The goal is to achieve a stable long term improvement of 3 dB or better down to 500 Hz with tuned signal-recycling, DC readout, and with an in-vacuum output mode cleaner.

A squeezed light source of the same design as described in Refs. 2 and 3, with RF frequencies compatible with the GEO detector, will be built this year in Hannover. The source will be tested and its long term stability with respect to an in-vacuum mode cleaner will be characterized at the Albert Einstein Institute. It will be installed at the GEO detector in the first half of 2009. At the same time an in-vacuum isolator and an output mode cleaner will be added. Most likely, the squeezed light source will have an automated phase control system and its spatial mode will be controlled by an auto-alignment system—in order to achieve long-term stability. After commissioning this upgrade GEO-HF plans to run continuously with squeezed light injection. We expect a shot-noise reduction greater than the improvement that can be achieved by doubling the laser power.

The squeezed light upgrade of GEO600 allows the H1 test to focus on noise, scattered light and sensitivity issues that can only be done on the LIGO interferometers, in particular below 500 Hz, and at a sensitivity level directly applicable in Advanced LIGO. It is equally important to be able to

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[1] Kirk McKenzie, Nicolai Grosse, Warwick P. Bowen, Stanley E. Whitcomb, Malcolm B. Gray, David E. McClelland, and Ping Koy Lam, *"Squeezing in the Audio Gravitational-Wave Detection Band,"* Phys. Rev. Lett. 93, 161105 (2004).

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

[3] 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.

demonstrate that one can squeeze the shot noise as it is to avoid degradation of the sensitivity at other frequencies.

Having the GEO600 effort preceding the H1 experiment significantly strengthens the outlook. We think that the compatibility of squeezed light injection with high displacement sensitivity and 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 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 2 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. 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.

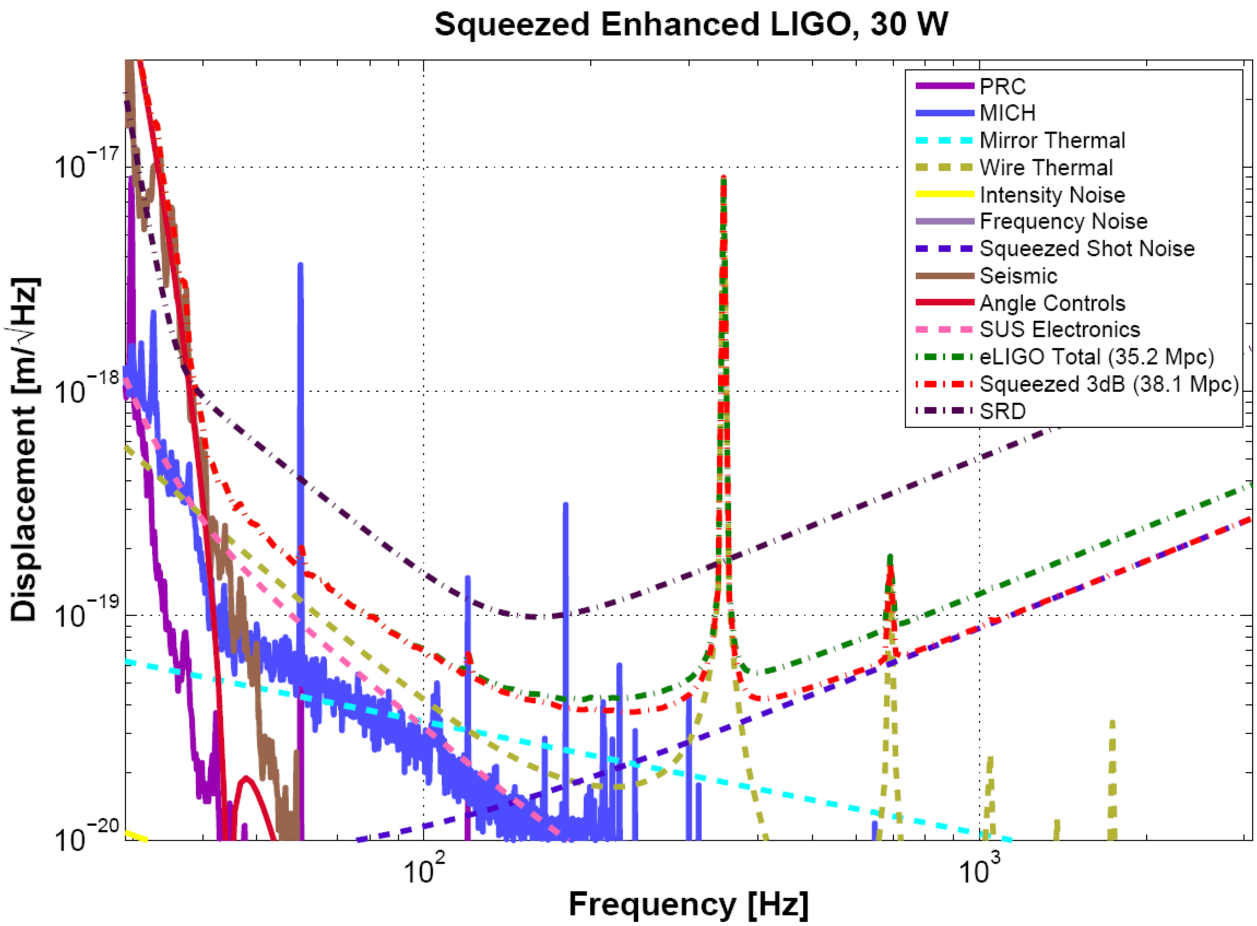


Figure 2 The projected sensitivity improvement of a squeezed light interferometer after Enhanced LIGO has been implemented. See text for a description of the individual curves.

3 Experiment

A schematic view of the experiment is shown in Figure 3.

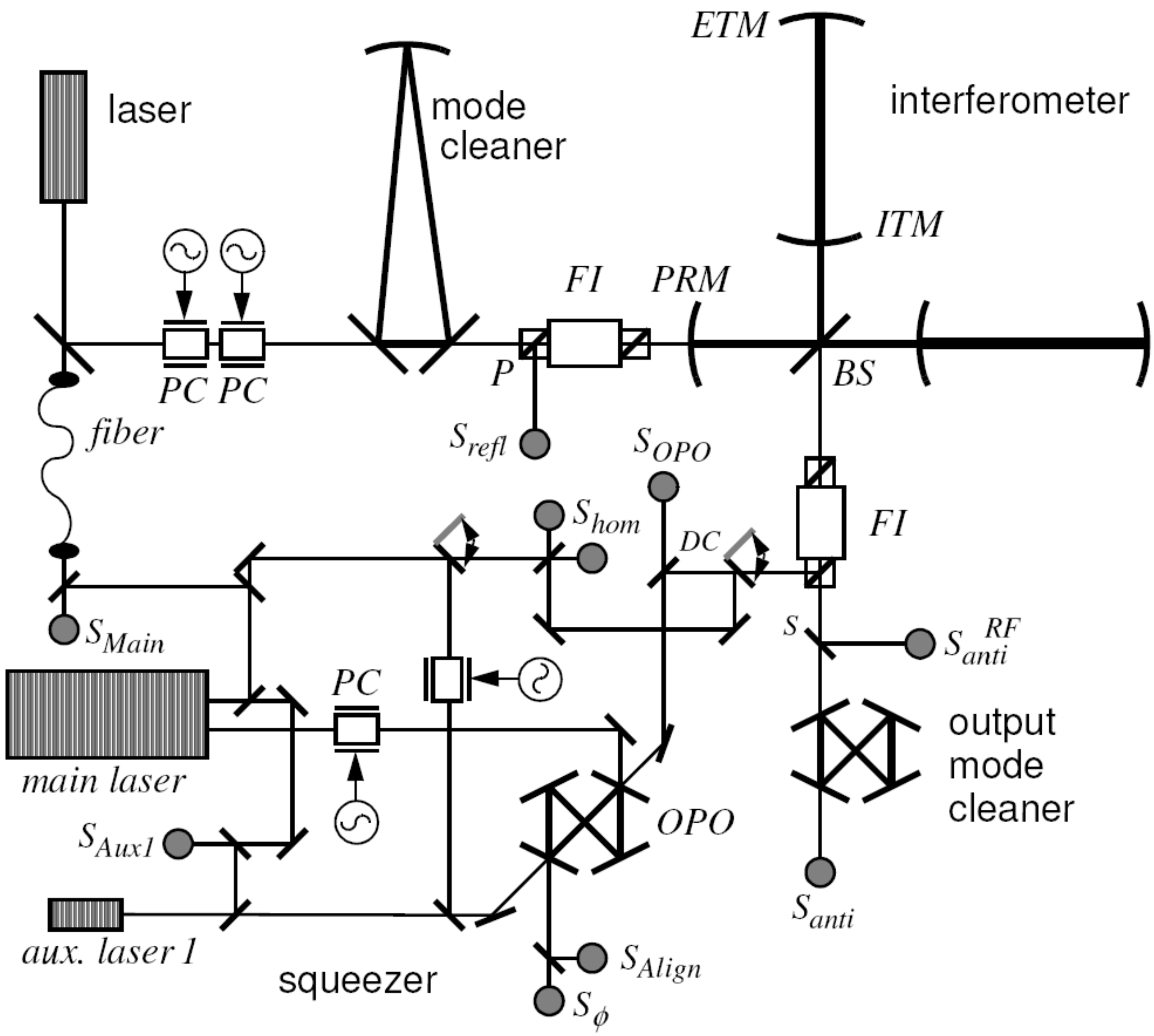


Figure 3 A schematic view of the squeezing experiment. Part of the interferometer laser light is launched into a fiber and brought to the squeezer where it is used to lock the main laser through S_{Main}. The frequency-doubled output is then sent to the optical parametric oscillator (OPO). In reflection S_{OPO} is used to lock the length of the OPO. The auxiliary laser 1 runs with a frequency offset and is locked to the main laser through S_{Aux1}. It can be combined with a probe beam from the main laser before it is injected into the OPO. In reflection S_{ϕ} and S_{Align} are used to lock the squeezer phase and to verify the alignment, respectively. 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. A homodyne detector S_{hom} is used to verify the squeezing power.

3.1 Baseline Design

We propose to build a new squeezer which follows standard LIGO design practice and which serves as a prototype for a squeezer suitable to be installed in advanced LIGO. After completing the H1 squeezer experiment the squeezer will be available for long term studies of reliability and maintainability. The electronics setup will be using a lot of the same components, circuit boards and remote controls as the advanced LIGO laser.

The squeezer will be installed near the anti-symmetric port. We propose to use a similar type of squeezer as has been demonstrated by the Hannover and ANU groups. 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 breadboard is a new squeezer table (SQT4) which will be installed next to HAM4 and opposite of ISCT4. We propose to take the currently unused ISCT3 and recycle it as SQT4.

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 re-entering the interferometer. Therefore, we have to inject the squeezed beam through an auxiliary port of the second polarizer of the Faraday isolator. The current Faraday isolator has high losses on the auxiliary ports and is not suitable for injecting squeezed light. We propose to modify the design of the advanced LIGO Faraday isolator and built a first unit ahead of time. We also propose to move the existing anti-symmetric port Faraday isolator to the injection path of the squeezer—in order to prevent light from the interferometer to reach the squeezer breadboard.

The squeezer breadboard will be assembled at MIT, ANU and in the LHO optics lab during S6. It will be fully tested and characterized by the time Advanced LIGO installation starts at LLO. The squeezer breadboard implements a frequency doubled Nd:YAG laser which delivers 1 W of green light and 100 mW of 1064 nm light. It will be locked to the main interferometer laser through a fiber. A fiber stabilization system will be used to suppress acoustic pick-up. An auxiliary laser is used to generate a frequency shifted subcarrier beam which is used to lock the squeezer angle as well as the relative phase between the local oscillator and the squeezed beam. An optical parametric oscillator (OPO) is used to generate the squeezed beam. The proposed configuration is a doubly resonant bowtie ring cavity with PPKTP as the non-linear crystal (see Appendix D).

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 Optical Layout

The optical layout is separated into the in-vacuum beam path and the squeezer breadboard.

3.2.1 In-Vacuum Beam Path

The optical layout of HAM4 is shown in Appendix A. The anti-symmetric port Faraday isolator has been replaced by a new Advanced LIGO Faraday which employs an additional thin film polarizer. The squeezed light beam *S1* is injected through the middle port on the south side door of HAM4. It will first pass through the old anti-symmetric port Faraday isolator which prevents light from leaving the vacuum. Injected light in the wrong polarization is guided back out through right hand port on the south side door of HAM4. This beam is intended to help recover the alignment into the interferometer. The in-vacuum beam path runs below the beam reduction telescope of the ITMX pick-off. It then zigzags around the beam reduction telescope of the anti-symmetric port before it enters the anti-symmetric port Faraday isolator through the rejection port of the thin film polarizer.

3.2.2 Squeezer Breadboard

The optical layout of the squeezer breadboard is shown in Appendix B. The size of the bread board is 5 feet by 3 feet. It contains the main doubled Nd:YAG laser which is locked to the interferometer light through a fiber. It contains an auxiliary laser which is locked to the main laser with a frequency offset. Both laser locking servos use the FSS circuit of Initial LIGO. The frequency-doubled light of the main laser is used to pump the OPO as well as to lock its length using the Pound-Drever-Hall reflection locking technique. The subcarrier generated by the auxiliary laser is injected into the OPO as well. The OPO will then generate a mirrored subcarrier at opposite frequency offset. By looking at the beat between the two subcarriers one can determine the squeezer phase and set it by adjusting a longitudinal PZT actuator in the frequency-doubled pump path. The two subcarrier beams will also enter the interferometer where they will beat with the local DC field at the anti-symmetric port to generate a signal measuring the local oscillator phase. This error signal is fed back to a longitudinal PZT actuator in the squeezed light injection path.

A homodyne detector pair is mounted onto the breadboard to verify the squeezing power. A probe beam from the main laser can be injected into the OPO to adjust alignment and make sure the OPO is doubly resonant.

There is no auto-alignment system planned for this setup. However, we plan to implement angular actuators on the squeezer breadboard to adjust the beam direction remotely.

3.3 Servo Controls

3.3.1 Laser Locking

The probe beam from the interferometer laser passes through two AOMs. It will be shifted in frequency by a total of about 160 MHz. This requires the main laser to be locked at an offset. The signal S_{Main} in Fig. 2 is demodulated by twice the AOM frequency and then fed into a frequency stabilization servo (FSS). As in Initial LIGO, the actuation is divided into a Pockels cell path for high bandwidth, a fast PZT path covering the intermediate bandwidth, and a slow thermal path for drift control. This should allow for a bandwidth up to 500 kHz.

The auxiliary laser is used to generate a subcarrier with an offset frequency. It is used to lock both the squeezer phase and the local oscillator phase. For this it needs to be locked to the main laser. The signal S_{Aux1} which is the interference between the main and the auxiliary laser fields is demodulated by the subcarrier offset frequency and is feed back to the auxiliary laser using an FSS. Again, a bandwidth of up to 500 kHz can be achieved with this setup.

3.3.2 OPO Locking

The OPO is doubly resonant and is locked by applying the Pound-Drever-Hall reflection locking technique on the green light. The signal S_{OPO} is demodulated by the OPO locking frequency and then fed back to one of the OPO mirrors mounted on a PZT. A bandwidth of a few kHz can be readily achieved.

The OPO is made doubly resonant with a birefringence wedge. The wedge itself is temperature controlled to about 1 ºC. A probe beam is used to align the wedge. A flipper mirror directs light from the main carrier field through a Pockels cell to the rear side of the OPO. It is modulated by the same OPO locking frequency. The corresponding Pound-Drever-Hall signal is measured by the signal S_{Align}. It can be directly compared to the OPO error signal S_{OPO}.

3.3.3 Squeezer and Local Oscillator Phase

The squeezer phase is the relative phase between the green pump light and the squeezed light generated in the OPO. It is locked using the subcarrier from the auxiliary laser. The subcarrier is injected into the rear of the OPO. Looking in reflection of the OPO one should detect a fraction of the injected subcarrier field as well as a subcarrier produced by the OPO at opposite frequency offset. The signal S_{ϕ} is therefore demodulated at twice the subcarrier frequency. It is fed back to a PZT mirror mounted in the green light path.

The local oscillator phase is the relative phase between the squeezed light and the interferometer light. It is locked by demodulating the signal S_{anti}^{RF} at the anti-symmetric port with the subcarrier frequency. It is then fed back to a PZT mirror mounted in the squeezed light path.

The squeezed light can be analyzed using a homodyne detector pair. A flipper mirror is used to deflect the squeezed light beam towards the homodyne detector. In this case the local oscillator phase is the relative phase between the squeezed light and the homodyne reference beam. However, the homodyne reference beam is just the fundamental carrier field. Therefore, the signal S_{hom}^{RF} can be used instead to lock the local oscillator phase.

3.4 Electronics

3.4.1 Block Diagram

A block diagram of the electronics is shown in Appendix C. The main blocks are the fiber locking, the main laser locking, the auxiliary laser locking, the OPO locking, the squeezer phase locking, the local oscillator phase locking and the angular controls. The block labeled auxiliary laser 2 locking is a contingency and will be discussed in the technical section.

3.4.2 Length and Frequency Controls

Most of the servo loops for the squeezer with the exception of the currently not implemented auto-alignment system are faster than what is supported by the LIGO digital controls. The development of fast digital servos would require significant effort and probably would involve programming a DSP or FPGA. Increasing the sampling rate will also increase quantization noise and may require more sophisticated whitening and dewhitening filters. We don't believe the squeezer setup is the best way to develop new controls hardware. Since no multiple-input multiple-output (MIMO) servo loops are required for locking length and frequency, our approach follows the one taken in Initial LIGO for the PSL and mode cleaner. The base plan is to use analog feedback controls networks with digital gains, offsets, signs, on/off switches, etc. As a matter of fact we are planning to use the same frequency synthesizers, RF distribution panels, demodulators, PSL frequency stabilization servo boards and mode cleaner boards as were used in Initial LIGO or are in development for Advanced LIGO.

Additional electronics will be required for a few longitudinal PZT actuators with their associated high voltage drivers. The baseline design uses PZT actuator stacks from Physik Instrumente.

3.4.3 Angular Controls

The baseline design for the angular actuators is to use the same PZT stacks as are currently used in Initial LIGO on the PSL periscope to steer the beam into the mode cleaner. We do not plan to implement an angular feedback controls system.

3.4.4 Fiber Stabilization

Advanced LIGO may require a fiber stabilization system to transport the laser frequency to the end stations. This system is currently in development and testing is in progress. We plan to use the same or a very similar system to stabilize the main squeezer laser to the interferometer input beam.

One of the currently tested fiber stabilization systems uses an acousto-optics modulator (AOM) at input to adjust the laser frequency launched into the fiber. It also uses a fixed frequency AOM at the output to shift the frequency of the return beam. By locking a voltage controlled oscillator (VCO) to the beat node between the returned beam and the injected beam a feed-forward system can be realized. The VCO frequency is divided by two and sent to the first AOM.

3.4.5 Remote Controls

The slow controls system has to have the capability to

- input and output binary status words at a rate of several Hz,
- input and output analog voltages at an update rate of several Hz,
- being able to implement slow PID loops and similar controls logic,
- being able to integrate with EPICS, and
- being usable in a stand-alone test stand.

The Initial and Enhanced LIGO slow controls hardware is based on VME bus. This will be no longer supported in Advanced LIGO. The Enhanced LIGO laser source implements a new Ethernet based slow controls system which is managed by a PC. It is interfaced to EPICS through a device support package. The baseline design for the slow controls system of the squeezer setup will use the same type of hardware and software from Beckhoff Automation LLC.

3.5 Technical Challenges

3.5.1 Optical Parametric Oscillator (OPO)

There are two OPO configurations currently under discussion: (a) a short linear cavity and (b) a bow-tie ring topology. Even so there are pros and cons either way; it was felt that most likely either solution can be made to work (Appendix D for more details). The GEO600 squeezer experiment will use a two-mirror OPO. A complementary approach at H1 may allow us to test both solutions and evaluate their potential for Advanced LIGO more thoroughly. We decided that ANU will prototype a ring laser configuration while AEI will continue with the linear cavity design. A final evaluation will take place in summer 2009 to see if either design can work. To switch back to the linear OPO design we would need an additional auxiliary laser to lock the OPO with light in the opposite polarization. A write-up describing the rational behind the OPO configuration choice can be found in Appendix D.

3.5.2 Second Harmonics Generator (SHG)

The main reason to choose the Diabolo laser system is that it starts with a low noise NPRO Nd:YAG laser and incorporates a SHG to produce 1 W of 532 nm light. It also delivers a probe beam at the fundamental frequency which is required for reference. Using a home-brew SHG adds flexibility in selecting modulation frequencies, which is not a problem for the H1 squeezer experiment. Building a SHG will require additional resources.

Due to the high infrared light intensity, this stage on the squeezing breadboard is probably one of the most critical ones regarding stray light issues. A really good mode matching into the SHG is recommended and all remaining back-reflected infrared light has to be dumped and shielded carefully. Optics of the highest quality should be used to minimize scattering. Since the Innolight Diabolo laser system design does not take these issues into account, a home-brew SHG topology allows better control of scattering. Alternatively, one might consider supporting Innolight with higher quality optics.

We propose to start with a Diabolo system because it is a readily available solution. We will always have the option to disable the internal SHG and use an external one. We will talk to Innolight to see if they can improve baffling and optics coatings. We will rely on the GEO-HF experiment to ensure that an external SHG will be available should it turn out to be needed.

3.5.3 Auxiliary Laser Requirements

A good argument to use an auxiliary laser instead of an AOM is the scattering issue. If one decides to use an independent—right from the beginning frequency shifted laser source—there would be absolutely no scattering at the main laser frequency from this additional laser source. The 1 Hz squeezing experiment at the AEI has already shown that AOMs can cause problem at the low frequency regime.

The auxiliary laser is needed to generate the subcarrier used to lock the squeezer phase and the local oscillator phase. In case of a linear OPO a second auxiliary laser would be needed to lock the OPO. Because of the bifringence of the non-linear crystal the frequency of the locking beam would have to be shifted by several 100 MHz or even a couple of GHz.

We propose to use a low power NPRO laser—such as the Innolight Mephisto—and lock it to the main laser of the squeezer using the existing frequency stabilization servo (FSS) electronics.

3.5.4 Fiber Stabilization

We are planning to use a probe beam from the main interferometer as the phase reference for the squeezer. This probe will come from the PSL table by default, but could also be picked off from any other port—such as after the mode cleaner. Since the main laser on the squeezer breadboard is locked to this probe beam, fiber noise and acoustic pick-up will degrade the coherence between the two lasers. Because the squeezer angle is locked to the anti-symmetric port beam through a PZT actuator in the injection path, starting with a clean reference beam may not be that important.

However, there are limitations both in range and bandwidth of the PZT actuator. It is clear that starting with a clean beam is always advantageous.

We propose to use a fiber stabilization scheme in the H1 squeezer setup. This makes it possible to lock the main laser on the squeezer table with a high bandwidth to the main laser of the interferometer and have a very stable reference beam. This also allows us to evaluate the H1 performance with and without fiber stabilization.

The baseline fiber stabilization scheme uses two acousto-optical modulators: one at the input to the fiber and one at the output. The output AOM is used to shift the return beam by twice the AOM drive frequency. This scheme avoids that back scattering in the fiber confuses the error signal. A voltage controlled oscillator is used to lock to the beat signal between the injected and returned light. By dividing this signal by 2 it can be directly fed back to the AOM at the input. This feed-forward scheme corrects path length fluctuations in the fiber by changing the laser frequency. Alternatively, one can use a single AOM either at the input or at the output, double pass it, look at the beat node in reflection and feed back to AOM through a VCO driver.

3.5.5 In-Vacuum Faraday Isolator

The Initial LIGO anti-symmetric port Faraday isolator is located in HAM4 after the beam reduction telescope. It will stay at this location for Enhanced LIGO. The light leaving the Faraday isolator will be split into an RF path going to ISCT4 and an OMC path going to HAM6. This Faraday isolator has all unused ports covered and will have to be exchanged for the squeezer experiment. It consists of a Brewster-angle calcite polarizer followed by a Faraday rotator, another Brewster-angle calcite polarizer and a lambda-half plate. The same Faraday isolator is planned to be used in Advanced LIGO, albeit it might be suspended. Brewster-angle calcite polarizers have a high throughput. However, in order to inject squeezed light we would have to go through two surfaces with s-polarization. This would add an unacceptable loss of about 30%. Our strategy is to work with Advanced LIGO to accelerate the design of the Advanced LIGO Faraday isolator and make sure it can be used for squeezed light injection. A first-article unit can then be installed for this experiment and later reused for Advanced LIGO.

3.5.6 Scattering Paths

Scattered light is a serious problem in squeezed light experiments. Even small amounts of scattered light can completely destroy a squeezed light state. Scattered light problems on squeezer breadboards have been solved in the past and we intend to achieve the same. For the H1 squeezer experiment there is the additional burden to inject the light into the interferometer. Injecting light from an external source into an instrument with the sensitivity of H1 can pose special problems.

We have two ways to address and mitigate scattering problems in the injection path of the squeezer: (a) the squeezer is set up on the opposite side of ISCT4 on HAM6 and (b) an additional in-vacuum Faraday will be installed in the injection path. A separate vacuum window is used to bring the squeezed beam into the vacuum. This window should not be shared with any other beam. The currently installed Faraday isolator at the anti-symmetric port needs to be replaced for the squeezer experiment. We can then reuse this isolator in the injection path. This will prevent light from the interferometer to exit the vacuum system, back scatter and re-enter the interferometer. A further mitigation technique which is currently under consideration is the installation of in-vacuum baffles between optics used by the squeezer injection and optical elements from the main beam path.

3.5.7 Long-Term Reliability

It is clear that long term reliability of the squeezer setup will be important for it to be adopted by Advanced LIGO. Long term stability is influenced by

- contamination of the OPO,
- reliability of the lasers,
- automatization of the setup,
- angular drifts which require a re-alignment, and
- range of actuators.

The first three points can be addressed in the lab and do not require an interferometer. The requirement for the actuator ranges can be measured in the GEO600 and H1 squeezer setups and can be addressed afterwards. Angular drifts may require an auto-alignment system. We plan to test this in the GEO600 setup.

After the H1 squeezer experiment is finished the squeezer breadboard will be available for long-term stability tests.

3.5.8 Squeezer Table on HAM4 (SQT4)

We looked into available space at LHO for mounting the squeezer experiment. The anti-symmetric port Faraday isolator is currently installed in HAM4. Beams for the anti-symmetric port (RF readout), the ITMX pick-off and the beamsplitter pick-off are leaving the in-vacuum table through the three main beam-line viewports of the north-side door. ISCT4 and its acoustic enclosure are located just next to the north-side door.

We propose to use the south-side door of HAM4 for the squeezer experiment. Both the center viewport and the viewport to the right (east) can be used. The right viewport is currently used by a camera and has a straight view to the anti-symmetric port Faraday. A beam reduction telescope is mounted to the very edge of the in-vacuum table. However, this telescope is mounted high so that there is enough space below to propagate the squeezer beam at normal beam height. This makes it possible to use the center viewport. Since the space below the telescope is not obstructed, an additional Faraday isolator will be mounted there as well.

There are basically two ways to place an optics table at the south side of HAM4. The traditional method would place the table at normal height and about 40 cm away from the viewport to clear the HAM seismic support beams. This would also require an ISC periscope to launch the beam into the vacuum chamber. The second method would place the table above the seismic support beams which allows it to move closer to the viewport. This also gives larger clearance between the table and the building wall.

We propose to use the second option. The minimum height to clear the seismic support beam is just above 46". ISCT3 is currently not used for main operations. It is a 4' by 10' optics table from Newport. Its thickness is 1' and it has a laser enclosure sitting on top of it. We propose to relocate this table to the south side of HAM4 with a new set of legs. We currently have a set of internally damped legs by TMC which are 34" high. We also have a set of 10" spacers which we can use to elevate the table to 44". The adjustment screws in the table feet allow for a maximum height adjustment of 1.5". To bring the bottom of the table to 47" height either longer screws can be used or an additional spacer inserted. This brings the table height to 59". This table is named SQT4.

To make the squeezer setup independent of the optics table we propose to layout the squeezer onto a 3' by 5' breadboard with a thickness of 4". This breadboard will then be set inside of SQT4 sitting on a set of elastomer feet. If we allow for an additional 4" for the elastomeric isolators, the breadboard height will be at 67". Using a 4" beam height the beam will be exactly at the height of the center of the viewport which is located at 71".

An electronics rack can be located next to the table on the HAM5 side.

3.6 Initial Alignment

Initial alignment of the squeezer should be straight forward. A beam entering from the squeezer breadboard into the squeezer port of the Faraday isolator will be reflected by the short Michelson and sent back to the anti-symmetric port. We plan to setup an alignment laser during the vent to install the modified Faraday isolator. This auxiliary laser will be co-aligned with the squeezer beam. The auxiliary laser beam will allow the alignment of all components in the squeezer injection path. The alignment will be compared to the main laser beam by looking at the light reaching the RF readout path at the anti-symmetric port. The auxiliary laser beam will be aligned correctly, if it overlays with the main laser beam both in orientation and shape. The orientation of the auxiliary laser beam will be marked at the location where it enters the vacuum window and in the far field by looking at the reflected beam from the first in-vacuum polarizer (beam path S2 in Appendix A).

The squeezer can be operated with a bright beam which will be used for initial alignment. After the vent the squeezer breadboard will be installed and aligned to the two alignment markers. This should give us a good initial alignment and make it possible to recover the full alignment quickly—once the interferometer is working again. A similar procedure is used for recovering the initial alignment of the main laser beam into the input mode cleaner; this works well.

The quality of the alignment and the mode matching can be assessed at the RF readout path of the anti-symmetric port. By measuring the parameters of the main laser beam and comparing it with the ones of the “bright” squeezer beam, one can estimate an overall loss factor due to beam mismatch. The RF readout port will also be used to lock the LO phase by beating the subcarrier field of the squeezer against the DC field of the interferometer. Using wavefront sensors the same beat node could be used for an auto-alignment system. However, we are currently not planning to install wavefront sensors on the H1 experiment (as opposite to the GEO600 setup).

The squeezer beam also needs to pass through the output mode cleaner. By monitoring the power in transmission of the output mode cleaner further inside into the alignment and injection efficiency can be gained. The injection inefficiency will look like a loss to the squeezer and, therefore, will limit the available squeezing. During operations we plan to orient the squeezer beam with the interferometer beam off by looking at the RF readout port first and by optimizing the squeezer field in transmission of the output mode cleaner second. Then, we relock the interferometer and operate the squeezer in the same orientation until alignment drifts become significant and require a re-alignment.

4 Cost and Schedule

4.1 Schedule

A detailed schedule can be found on the web[4].

4.1.1 Outside Constraints

The Advanced LIGO schedule shows the shutdown of the first site—LLO in our planning—on February 15th, 2011. The shutdown at LHO is scheduled on October 3rd, 2011. This opens a window of roughly 7.5 months for the H1 squeezer experiment.

4.1.2 Overview

The proposed schedule is shown in Table 1. There are about two and half 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 six months for the actual experiment.

Table 1: Summary of proposed schedule

	Task	Description	Dates
1	Squeezer Prep	Build and characterize squeezed light source on a bread board in optics lab	9/2008 – 2/2011
2	Faraday Prep	Build new Faraday	2010
3	Modeling	Model squeezer performance and develop noise budget	2009 – 2012
4	Vent	Install in-vacuum Faraday and steering optics	2/16/2011 to 2/22/2011
5	Squeezer installation	Install squeezer at final location and install fiber for squeezer beam	2/15/2011 to 3/14/2011
6	Measurements	Measure interferometer performance with squeezer installed, refine noise budget	3/15/2011 to 10/2/2011
7	Report	Remove squeezer, finish modeling and prepare report	10/3/2011 to 4/2/2012

4.1.3 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 for work to be started in the same year. A second decision point is located on August 24th,

[4] http://www.ligo-wa.caltech.edu/~sigg/Squeezing/SqueezerPlan2.pdf

2010, halfway into the sixth science run before the work on the Faraday isolator starts. At this time it should be clear if the commitment to go ahead is compatible with the Advanced LIGO progress.

4.1.4 Preparation and Testing

While the 6^{th} 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.

4.1.5 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 six 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 without degrading performance in other frequency bands.

4.2 Person Power

The current planning assumes that the person-power resources listed in Table 2 will be available.

Table 2: Estimate of required person power.

	Item	**Task**	**Time**
1	Grad. student/postdoc	Laser setup/commissioning	1 FTE/3 years
2	Grad. student/postdoc	OPO construction/commissioning	1 FTE/3 years
3	Grad. student/postdoc/scientist	Homodyne detector	2 months
4	Scientist	Task lead/organizational	0.25 FTE/3 years
5	LIGO scientist/EE	Electronics	0.5 FTE/2 years

6	Scientist/postdoc	Commissioning support	8 months
7	Optical engineer	Faraday isolator	2 months
8	ANU scientist	OPO construction	

We will need 2 experienced graduate students between the beginning of next year and the end of the project. A better mix may be 2 slightly less experienced graduate students and 50% of a postdoc or scientist.

4.3 Cost Estimate

A detailed cost estimate can be found on the web[5].

A summary of the cost estimate is presented in Table 3. This estimate only includes equipment costs and travel. The main equipment costs are associated with buying the components for the squeezer. The contribution from ANU in building the OPO is estimated to be valued at 13k$. The AEI contribution in building the homodyne detector is estimated to be valued at 3k$. The assumption is that the Faraday isolator at the anti-symmetric port will be the Advanced LIGO one and will be paid for by Advanced LIGO funds. If we have to switch the OPO configuration to a linear cavity, an estimated additional 50k$ will be required.

Table 3: Cost estimate summary (excluding salaries).

	Item	**Estimated Costs (k$)**
1	Optics	322
2	Electronics	121
3	Travel	59
4	ANU contribution	-13
5	AEI contribution	-3
6	Advanced LIGO contribution	-25
	Total without travel	**418**
	Total with travel	**477**
7	Technical risk: OPO topology	50

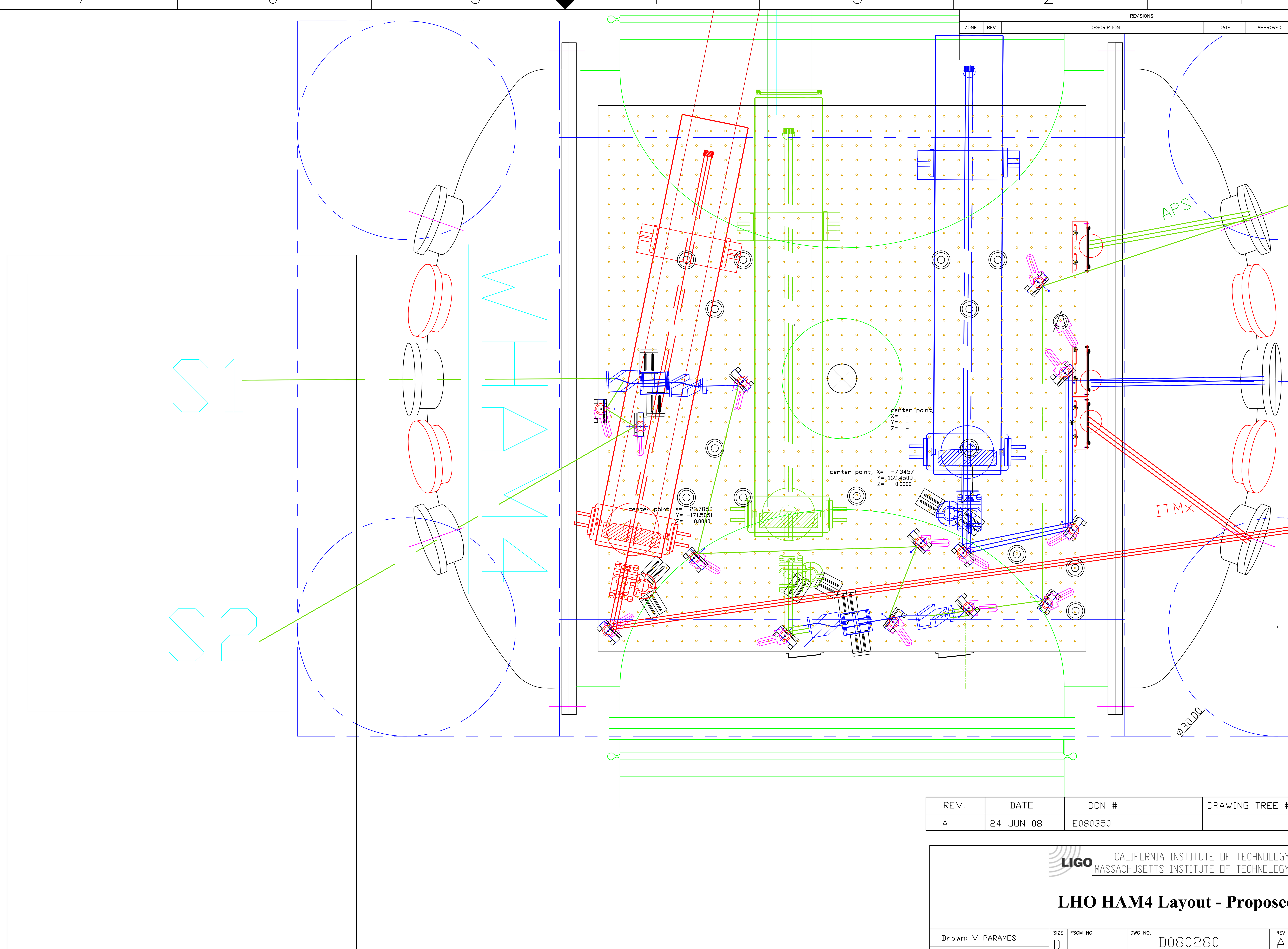
[5] http://www.ligo-wa.caltech.edu/~sigg/Squeezing/EquipmentList.xls

Appendix A Optical Layout of HAM4

Appendix B Optical Layout of Squeezer Breadboard

Appendix C Electronics Diagram

Appendix D OPO Write-up



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A	24 JUN 08	E080350	

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LHO HAM4 Layout - Proposed

Drawn: V PARAMES

Date : 20 MAY 08

SIZE	FSCM NO.	DWG NO.	REV
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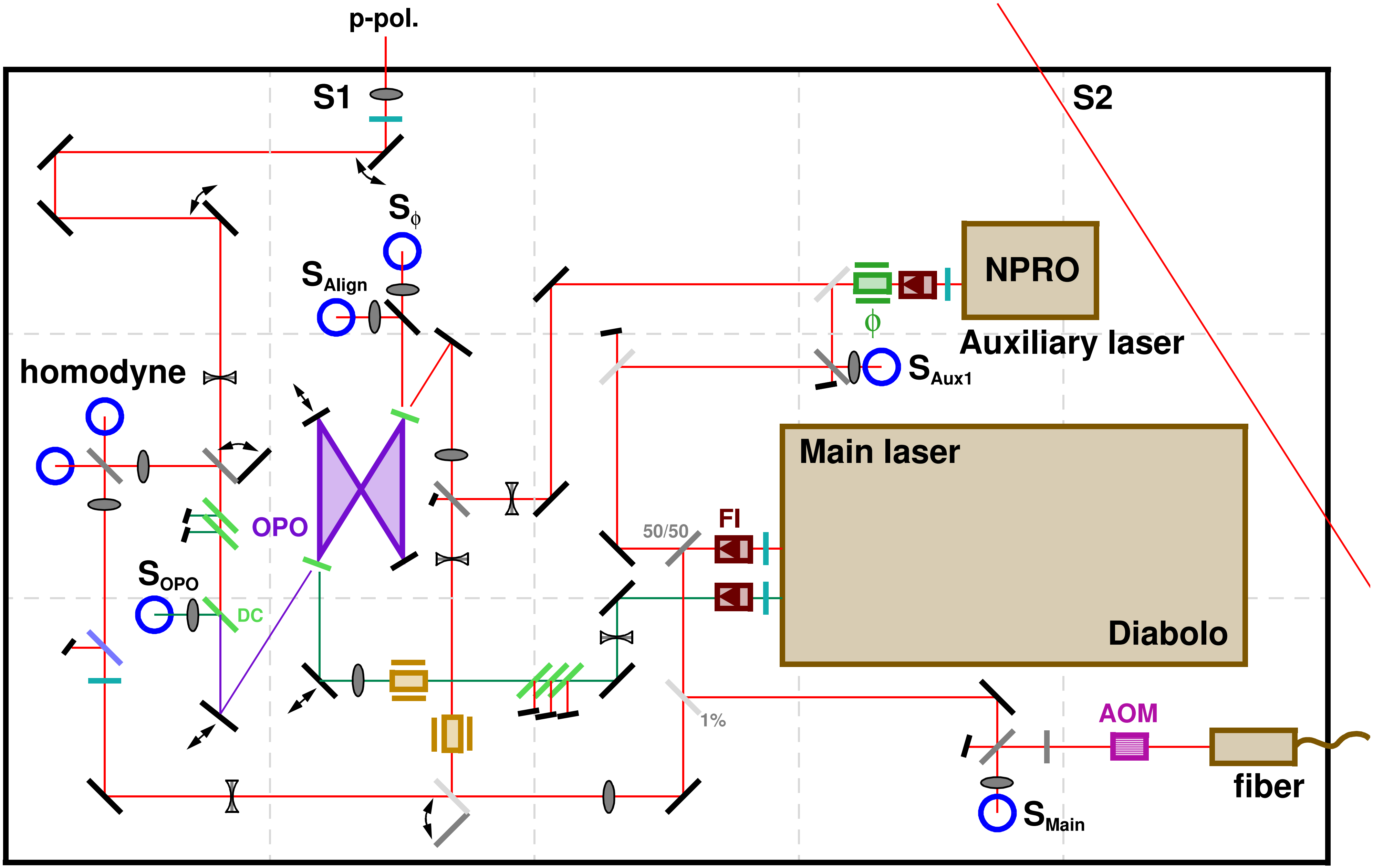
SCALE SHEET



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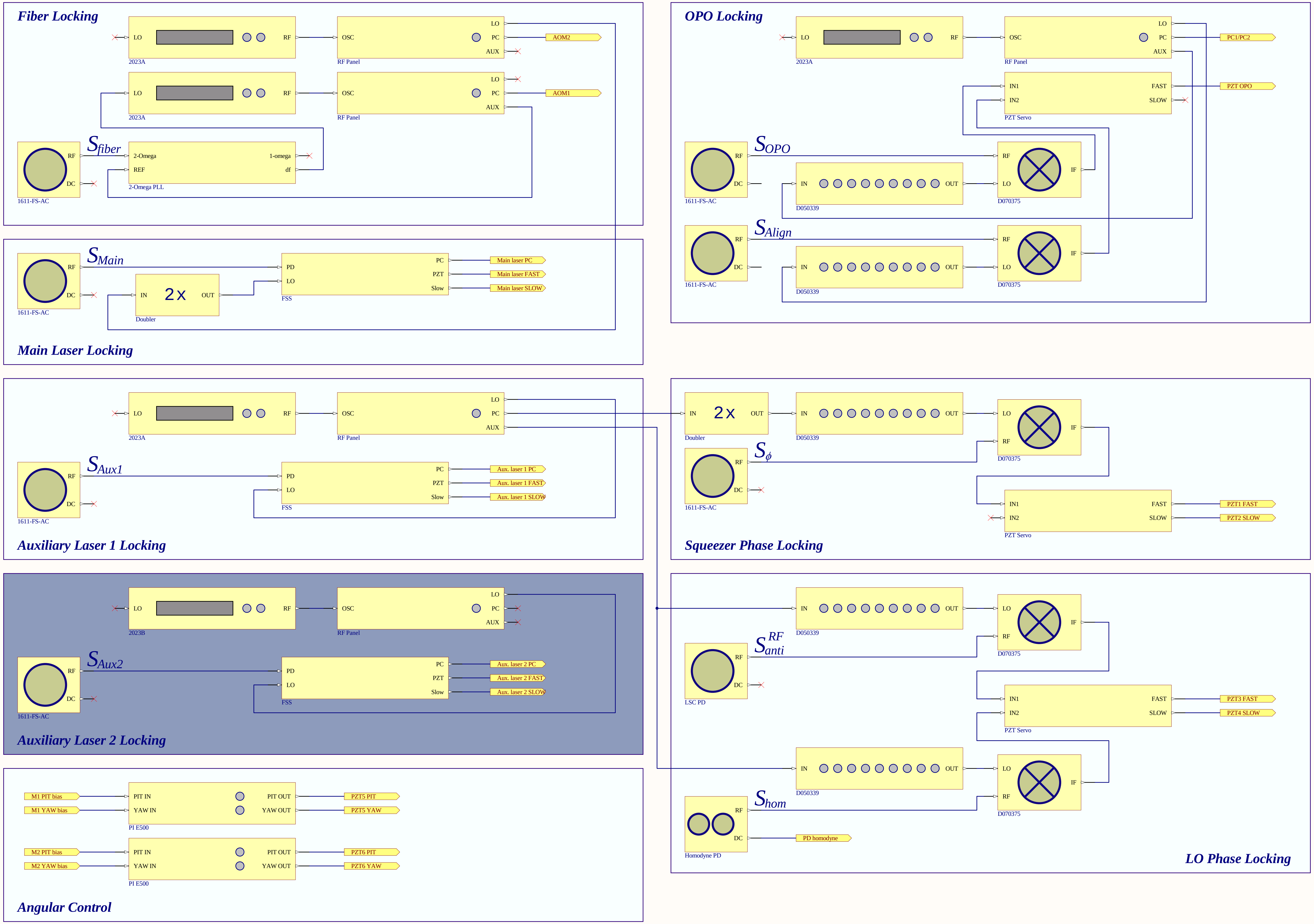

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Date: 8/13/2008		Sheet 1 of 1	
File: C:\User\..\System1.SchDoc		Drawn By: Daniel Sigg	

Discussion of the LIGO Squeezer Design

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(Dated: June 27, 2008)

This paper presents a summary of information for the LIGO H1 squeezer design.

I. EFFICIENCY OF SQUEEZING

The efficiency of squeezing $\eta_{\rm sqz}$ as described in the equation below, depends on five efficiency parameters:

$$\eta_{\rm sqz} = \eta_{\rm intra}\eta_{\rm esc}\eta_{\rm lin}\eta_{\rm homo}\eta_{det} \quad (1)$$

- $\eta_{\rm intra}$ is dependent on the intra-cavity nonlinear process. For OPO operating at threshold, $\eta_{\rm intra} = 1$. In a typical experiment, operating the OPO at 80% threshold is sufficient to get $\eta_{\rm intra}$ near enough to unity. In the idealized model for squeezed state generation, a below threshold optical parametric oscillator (OPO) will produce near perfect squeezing down to zero Hertz.

- $\eta_{\rm esc}$ is the escape efficiency. This is approximately equal to the ratio of output coupling rate $\kappa_{\rm out}$ to the total cavity decay rate $\kappa_{\rm tot}$. In a typical experiment, we can set the coupling to around 10% and keep other cavity losses to less than 1%.

- $\eta_{\rm lin}$ is the transmission efficiency from the cavity to the final detection stage. This linear loss is typically around 0.1% per optical surface.

- $\eta_{\rm homo}$ is the homodyne detection efficiency. It is equal to the square of the interferometric fringe visibility. With a good setup, $\eta_{\rm homo}$ can be higher than 99%.

- η_{det} is the detector efficiency of the photodetectors. Calibration of photodiode efficiency is poor and so far measurements suggest a typical η_{det} of $(94 \pm 4)\%$

II. CRYSTAL MATERIALS

There are a variety of nonlinear crystals that can be used for OPO/SHG between 532/1064nm. The materials investigated are:

- PPKTP: This material has very high nonlinearity via the use of the d_{33} of KTP. Best result obtained was > 9 dB of squeezing by Tokyo University. Grey tracking was a known problem when PPKTP is used near the UV wavelength (795/397 nm). To date, we have no data on grey tracking at 1064/532 nm.

- MgO:$LiNbO_3$: Although this material has lower nonlinearity compare with PPKTP, it has lower material loss. The material is also more robust than PPKTP. MgO doping is used to increase the photo-refractive damage threshold. Best results obtained was > 10 dB of squeezing by AEI Hannover.

- PPSLN (Periodically Poled Stoichiometric $LiNbO_3$) and PPSLT (Periodically Poled Stoichiometric Lithium Tantalate $LiTaO_3$) are suppose to have high nonlinearity and be more robust than PPKTP. To date, several experiments in different labs have failed to obtain large squeezing. This is perhaps due to the imperfection of the poling.

- Walk-off compensated Type-II KTP (where the signal and idler beams are polarization non-degenerate). A Type II squeezer produces twin beams that can be "difference squeezed". This scheme is not useful for the current application.

III. RING CAVITY VS STANDING WAVE CAVITY

A. Ring (Bow-tie) cavity

The most widely used type of ring cavity is the bow-tie cavity, due to the necessary condition of an even number of reflections per cavity round trip, which avoids the inversion of any spatial inhomogeneity within the cavity in situations where spatial mode quality is critical. The advantages of using a bow-tie ring cavity for squeezing are:

- Inherent isolation to backscattered light from the local oscillator of the detection system (or light from the gravitational wave detector dark port), which can spuriously seed the OPO.

- Faraday isolators were required to reduce backscatter and prevent spurious of the OPO for standing wave cavities. The use of Faraday isolators can add considerable optical loss, typically 5-10% single pass. With some effort, considerably less loss ($< 1\%$) should be achievable.

- The traveling wave characteristic makes the phase matching condition less dependent on temperature. This is due to the absence of possible interference set up by the forward and backward passes of a double pass standing wave cavity.

- Bowtie configuration minimizes astigmatism. For small angle reflections, typically around 6-8 degrees from normal incidence, astigmatism is negligible.

B. Standing wave (Hemilithic) cavity

The type of standing wave cavity commonly used for squeezers is the hemilithic linear cavity. The advantages of using a hemilithic cavity for squeezing are:

- Fewer reflecting surfaces, thus having lower loss
- Single air/crystal interface, yet good operational flexibility
- Negligible spatial and polarisation distortion through its normal incidence operation

IV. DOUBLY RESONANT VS SINGLY RESONANT

Singly resonant cavities for degenerate OPO refer to a squeezer that is only resonant for the combined signal and idler field (otherwise known as doubly resonant for Type II system). In contrast, doubly resonant systems are that which resonate the combined signal and idler field and also the second harmonic pump field. The advantages of a double resonant OPO versus a singly resonant OPO are:

- The simplicity of obtaining a cavity error signal. The pump field can be used to readout the cavity length error signal and no sub-carrier field is required.
- Assurance of perfect mode matching of the interacting fields. Since the harmonic and fundamental fields share the same optical cavity, the ratio of the waist sizes is $\sqrt{2}$ (the fundamental waist is larger than the harmonic) which is exactly the optimal relative waist sizes for χ_2 nonlinear interaction.
- Spatial components of the pump field that are not matched to the cavity mode will be rejected from the cavity, thus photothermal effects induced by the pump light and nonlinear effects like GRIIRA are minimised.
- The pump field amplitude is resonantly enhanced, giving a higher nonlinear gain for the same input pump power. This allows the possibility of increasing the transmission of the output coupler at the fundamental frequency to increase the escape efficiency.

There are also disadvantages associated with doubly resonant OPO, which require mitigation to operate effectively. Namely:

- The intra-cavity dispersion of the fundamental and harmonic fields causes the resonance frequencies to be offset. In this case, when co-resonance does not occur, nonlinear interaction is interferometrically suppressed.
- The photothermal effect associated with absorption of the pump field in the nonlinear crystal. This can cause length instabilities such as optical bi-stability.

V. PROPOSED DESIGN FOR H1 SQUEEZER

We propose to use a doubly resonant bowtie cavity with PPKTP as the squeezer for H1. Considered are the following parameters:

- **Polarization:** PPKTP is quasi-phase matched. This means that the signal, idler and pump fields all have the same polarization. The fields should be s-polarized, since reflection via dichroic filters and mirrors are less lossy for s-polarization.
- **Beam waist:** The Boyd-Kleinmann factor can be used to calculate the optimal beam waist of a squeezer. Nevertheless, the idealized calculation does not take into account parasitic effects which usually result in larger waists being optimal. We propose to use a waist of $\approx 38\mu$m for the 1064 nm field. The beam waist of the second harmonic field is $\sqrt{2}\times$ smaller than the 1064 nm field.
- **Dispersion compensation:** The reflections at mirrors from dielectric coatings will produce a differential phase shift between the pump and fundamental fields. Dispersion compensation is required to co-resonate both fields. We propose to use a PPKTP with flat-wedge surface geometry for dispersion compensation. The wedge should be between 1-2 degrees.
- **Actuation of cavity length:** Control of cavity length is done via a single PZT with a locking bandwidth of 20 kHz. If needed, a high speed PZT coupled with Molybdenum rod can extend the locking bandwidth to around 200 kHz.
- **Temperature control:** A Newport temperature controller series 3040 can be used to control the crystal phase matching temperature accurate to ± 1 mK (long term stability).
- **Optical Path Length:** Typical FSR of bowtie squeezers are around 400 MHz. This is equivalent to a round trip perimeter of 70 cm.
- **Geometry of the bowtie**: The proposed length of the bowtie unit is around 200 mm. All mirrors have a reflection angle of 6-7 degree from normal incidence. This angle is a trade-off between minimizing astigmatism and maximizing the ease of access for retrieving the reflected beams.
- **Finesses/ Linewidths:** We aim to have Finesses of $\mathcal{F} = 50$ for the 1064 nm field and $\mathcal{F} \approx 100$ for the 532 nm field. The optimal Finesses of a squeezer is very dependent on the material quality of the nonlinear crystal. Harmonically coated output couplers with a range of reflectivities is needed for optimizing the performance of the squeezer. Typically, the stated Finesses require 1064 nm reflectivity of around 90% and a 532 nm reflectivity of around 95%. These will give a 1064 nm linewidth of 8 MHz. ie. the squeezing will have a 3 dB linewidth at 8 MHz.

Appendix E Differences between the H1 and the GEO squeezers

The topologies of the H1 and the GEO squeezers are basically the same with the exception of the OPO. The GEO project wants a higher squeezing level and therefore implements mode cleaners to make sure clean beams are entering and leaving the OPO.

ANU has operated both hemilithic and bow-tie OPO squeezers for many years. The AEI design is a mature technology, based on the system developed at ANU with the main change being the use of coherent control. This does not affect the squeezer performance per se, but it avoids seeding because a degenerate seed couples in noise. The AEI system has been nicely engineered and the ANU design needs to achieve the same product quality.

A stable bow-tie squeezer has already been demonstrated with more than 6.5 dB of measured squeezing. In other words both designs will meet the specifications as defined in this document. We do not know which geometry will work better when coupled to a suspended interferometer. But, we have reasons to think the bow-tie is a better option. Testing the linear cavity on GEO600 and the bow-tie on H1 is therefore the best way to proceed.

Due to the difference in the optical geometry and in the number of optical components of the squeezer cavities, most likely (a) the H1 squeezer will produce less scattering into the interferometer, whereas (b) the GEO squeezer should show less long-term drifts and will have less loss inside the cavity which potentially should allow for higher degrees of squeezing and for squeezed states of higher purity. At the moment it is not clear, if (a) or (b) will be more important for squeezed light injection in Advanced LIGO.

The current baseline calls for a commercial SHG to be used in the H1 test, whereas the GEO squeezer will use an in-house design. Using a commercial product in H1 is purely due to convenience. However, we may loose some of the flexibility to design exactly what we need. This is still under consideration and copying the AEI design is the current backup plan.

GEO also wants long term running, so a WFS system is planned from the beginning. Also, some of the component choices are different. For example, we are planning to use LIGO style electronics (which tends to be a little pricey) wherever we can.

The GEO squeezer setup is looking for more ambitious squeezing performance than the H1 experiment. The GEO squeezer breadboard has a goal of 12 dB of squeezing, but this is before the photodetector efficiency is added. After adding the losses in the interferometer path, the estimated shot noise improvements are 6 dB. The H1 experiment only promises 3 dB of squeezed shot noise. The main losses in the H1 system will come from the output mode cleaner, the new DC readout detectors and the Faraday isolators. We will have neither the time nor the resources to change any of these. If the additional losses are as high as 30%—which we considered an absolute worst case—, this will limit us to 3 dB of squeezed shot noise. Even so not explicitly mention, the squeezer breadboard itself needs to produce at least 6 dB of squeezing as measure by its homodyne detectors. We believe the time on H1 is better spent proofing that we do no harm rather than go for a record. It is clear that in Advanced LIGO 6 dB of overall squeezing would be a lot more interesting. We will have some idea from the GEO setup how realistic this is. We consider the 3 dB of squeezing in H1 a requirement rather than a goal.

At the current time it is unclear, if the squeezer built for the H1 test will be the final Advanced LIGO squeezer. Although, it will inform the final design and diagnose issues with coupling squeezers to LIGO. However, many of the components will be reusable.