Installation and Characterization of the Advanced LIGO 200 Watt PSL

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Background and Motivation

Albert Einstein's published his General Theory of Relativity in 1916, shifting the view of gravitation away from the well established laws of Sir Isaac Newton. Among many other phenomena, Einstein's theory predicts the existence of gravitational waves. According to Einstein, space-time is not "flat" as described by Euclidean geometry. In fact, objects with mass cause space-time to curve and warp proportional to the amount of mass the object contains. Gravitational waves are the result of bodies of mass accelerating, effectively creating "ripples" of space-time much like the ripples in a pond. When a gravitational wave passes a test mass, the mass contracts in one direction and expands in the orthogonal direction. The expanded direction is then contracted and the contracted direction expanded. The effect of a full wave period of a gravitational wave is depicted in Figure 1 below.

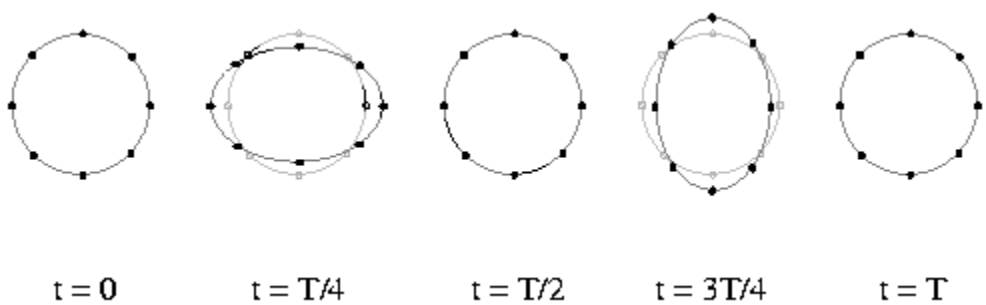


Figure 1 The effect of a gravitational wave on a circular ring over one wave period, T.

The amplitude of the gravitational wave is given by its strain, which is the change in length of an object due to the gravitational wave divided by the rest length of the object.

$$h = \frac{\Delta L}{L}$$

Any gravitational waves expected to reach Earth, however, are expected to be on the order of $h \sim 10^{-19}$ or less. This is an unimaginably small number and requires a very precise instrument in order to detect such a wave. The orthogonal nature of the test mass displacement lends itself to the use of a Michelson interferometer, which happens to be an extremely precise instrument as well. The Michelson interferometer operates on the principle of wave interference of light, which occurs on the nanometer

scale for visible light. A simple Michelson interferometer is shown below in Figure 2. If the two arms of the interferometer are the same length, the light returning to the beamsplitter will be in phase and the light will interfere constructively. If the two arms are not the same length, the light at the beamsplitter will be out of phase and interfere destructively. Thus a gravitational wave incident on the Michelson interferometer will produce a sinusoidal signal in light intensity at the detector.

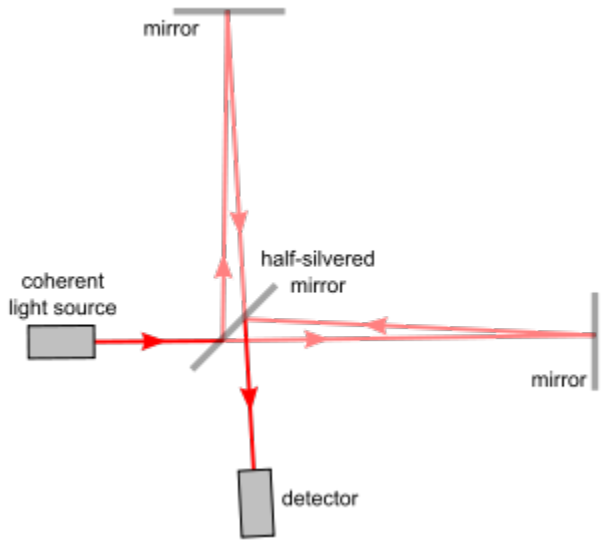


Figure 2 A schematic of a simple Michelson interferometer.

LIGO (Laser Interferometer Gravitational wave Observatory) is a set of large interferometers operated by a collaboration of physicists around the world with the sole aim of detecting these gravitational waves. LIGO has operated for several years and has undergone a series of extensive commissioning periods in order to increase the sensitivity of the interferometer and consequently increase the chance of detecting a gravitational wave. The current sensitivity of LIGO lies around $h \sim 10^{-19}$, which translates into one wave detection every couple years. Labs around the world, however, are researching new techniques of interferometry, planned to be installed in Advanced LIGO (AdvLIGO) in the next couple years. These upgrades are expected to increase the sensitivity to $h \sim 10^{-22}$, which should detect a gravitational wave once every couple days.

The remainder of this paper focuses on one such upgrade currently under development at the Max Planck Institute in Hannover, Germany. In order for LIGO to expect to detect any gravitational waves, the laser must satisfy two main criteria. First the laser must be ultra stable, because fluctuations in laser parameters will produce fake gravitational wave signals. Second the laser must be powerful, because the signal to noise ratio increases with the square root of the light intensity. LIGO currently uses a 35

Watt 1064 nm solid state laser, which is sufficient for the current sensitivity level. In order to reach AdvLIGO sensitivity level, however, the laser intensity must be increased to 200 Watts. This poses quite a problem for LIGO as 200 Watt ultra stable, or single mode, lasers are not currently available and so must be developed. In response, the Laser Zentrum Hannover (LZH) developed a 200 Watt laser more stable than any other 200 Watt laser in the world. Further stabilization is required, though, and gives rise to the Pre-Stabilized Laser system (PSL). The PSL consists of optical systems to further minimize laser fluctuations in intensity, frequency, spatial profile, and pointing, providing the high power single mode laser required to reach sensitivity levels expected in AdvLIGO.

Theory

In order to reach AdvLIGO sensitivity, the Pre-Stabilized Laser system must minimize laser fluctuations in intensity, frequency, spatial profile, and pointing. This is accomplished with several feedback loops from multiple optical systems. Beside laser stabilization, the PSL also serves as diagnostic tool. A Diagnostic Breadboard (DBB) is used to measure laser parameters in order to determine whether the optical systems in the PSL are working.

The frequency stabilization loop utilizes a reference cavity and the Pound-Drever-Hall technique. The reference cavity is a simple Fabry-Perot cavity with a fixed length, L. The cavity is held in vacuum and fixed to the optical bench so that L is constant. The Fabry-Perot cavity reflection and transmission coefficients then depend only on the wavelength of the light incident on the cavity. When the cavity is on resonance, T=1 and all the light is transmitted. Just off resonance, T<1 and a small fraction of the light is reflected. A plot of the reflected intensity near resonance is plotted in Figure 3 below.

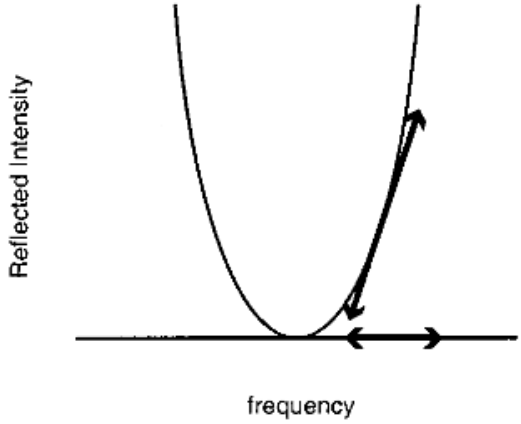


Figure 3 Reflected intensity near the resonance frequency of a Fabry-Perot cavity.

Since the reflected intensity is clearly an even function about the resonance frequency, it does no good to simply measure the reflected intensity. If the frequency is modulated and the reflected intensity is then multiplied with the modulation signal, the DC offset of the resulting signal is then an odd function about the resonance frequency. This signal can then be used to determine if the incident light on the cavity is on the left or right side of resonance and subsequently adjust the laser frequency accordingly. Figure 4 shows the setup of the Pound-Drever-Hall frequency stabilization loop.

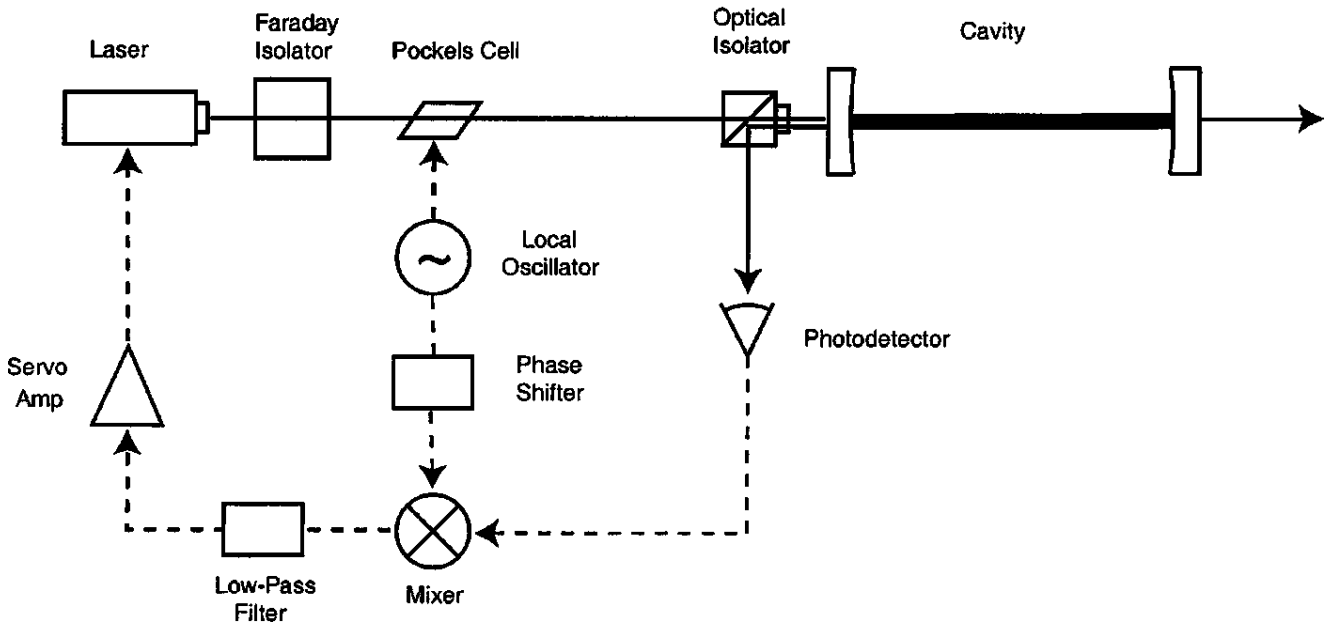


Figure 4 Frequency stabilization using a reference cavity and the Pound-Drever-Hall technique.

The laser first passes through a Faraday isolator which acts as an optical diode to prevent any reflected light from reentering the laser. The light then passes through a Pockels cell which modulates the frequency with a modulation frequency given by the local oscillator. Next the light passes through an optical isolator and into the cavity where the resonant light passes through and off resonant light is reflected back towards the optical isolator. The reflected light gets redirected to the photodiode that measures the reflected light intensity. This signal is multiplied with the local oscillator at the mixer. The local oscillator first passes through a phase shifter, however, to account for the phase the light picks up traveling through the cavity. The multiplied signal is sent through a low pass filter in order to extract the DC offset. This signal is then sent through an amplifier and finally fed back to the laser to shift the frequency closer to resonance by adjusting the temperature of the laser. The result is a pure single frequency laser beam in transmission through the Fabry-Perot cavity.

The intensity stabilization loop is accomplished in three ways. A long term loop prevents slowly varying intensity shifts due to thermal fluctuations, a fast loop filters out quickly changing intensity fluctuations due to quantum effects in the laser, and an ultra fast loop filters intensity fluctuations at radio frequencies. Both loops start with a photodiode that continually measures the intensity of the laser light. The long term loop feeds back to the input pump light to the laser because the intensity of the pump light determines the intensity of the output light. This is a slow process and hence is only used for long term thermal fluctuations. The fast loop utilizes an acousto-optical modulator (AOM) to stabilization light intensity up to ~100 kHz. A diagram of an AOM is shown below in Figure 5.

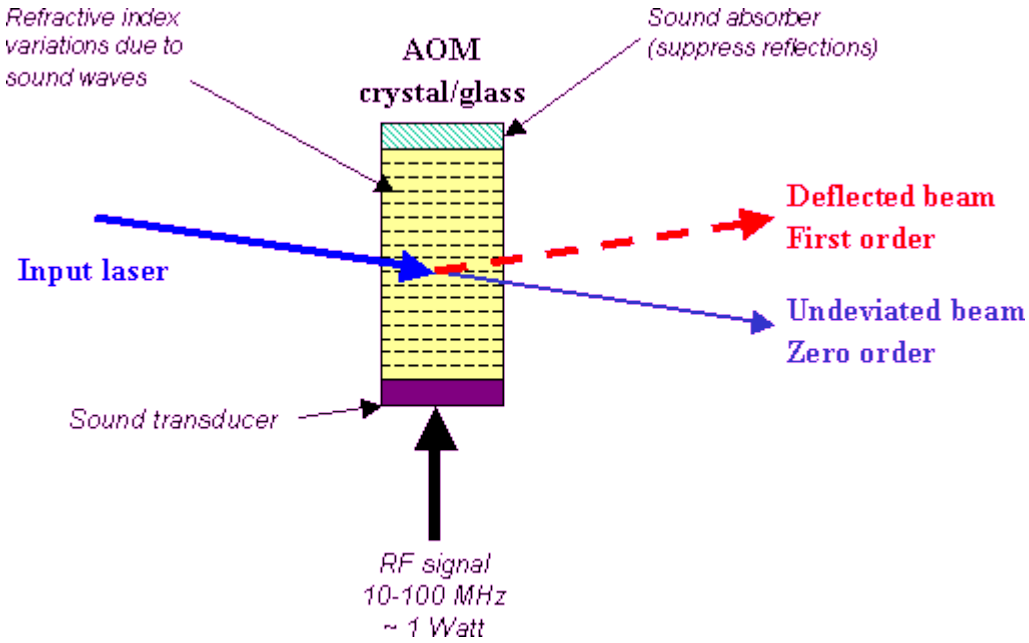


Figure 5 Diagram of an acousto-optical modulator.

An AOM works using the principle of interference similar to Bragg diffraction. A radio frequency modulation signal is fed to a sound transducer that is connected to a crystal or glass. These sound waves cause the refractive index to vary which in turn causes the input laser to interfere with itself and deflect a fraction of the beam at an angle, θ. The fraction of light deflected is determined by the amplitude of the modulation signal. Since the intensity of the input light is known from the photodiode, the intensity of the undeflected beam can be held stable by feeding back to the amplitude of the modulation signal.

The radio frequency intensity stabilization is contained within the spatial profile and pointing stabilization. These three parameters are stabilized with a special type of optical cavity which is named

the Pre-Mode Cleaner (PMC). The diagram of the cavity is shown in Figure 6.

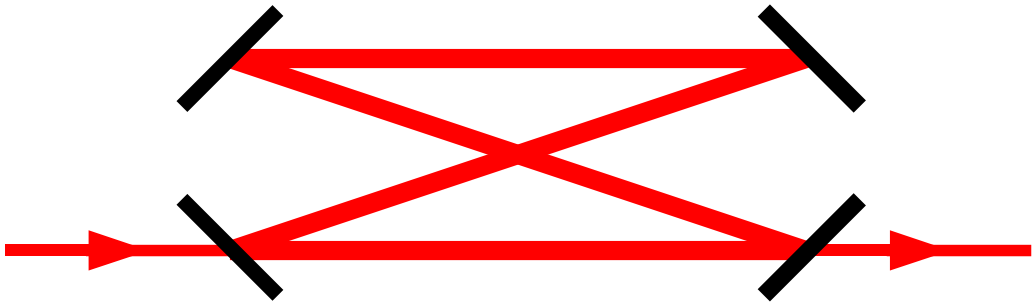


Figure 6 Diagram of the PMC.

The spatial profile is determined by the length of the cavity. An actuator is placed on one mirror and adjusts the length of the cavity so that the fundamental Gaussian profile is transmitted. The feedback loop is the same as the Pound-Drever-Hall technique mentioned above with the exception that signal is fed back to the actuator instead of the laser. The PMC is then locked on one laser profile, specifically the fundamental Gaussian mode. The pointing is stabilized by the PMC by carefully designing the cavity such that there is only one closed path for the light. This forces the light to exit in the same direction no matter how the light enters the cavity. The radio frequency intensity fluctuations are filtered out by the PMC because the light takes a finite time to build up in the cavity. As a result, the cavity cannot respond to changes in the radio frequency range and these fluctuations are minimized.

Installation

The schematic for the Advanced LIGO Pre-Stabilized Laser system is shown below in Figure 7.

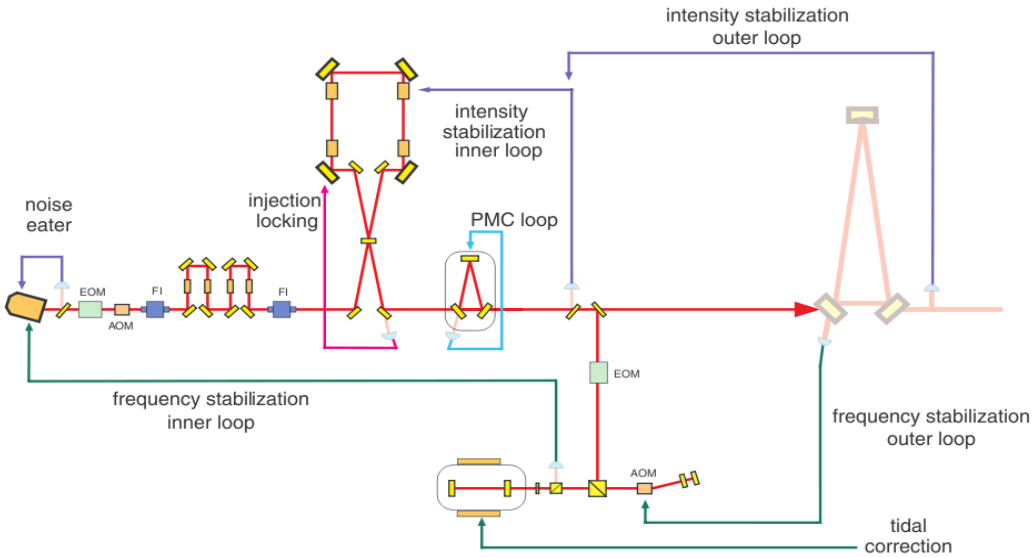
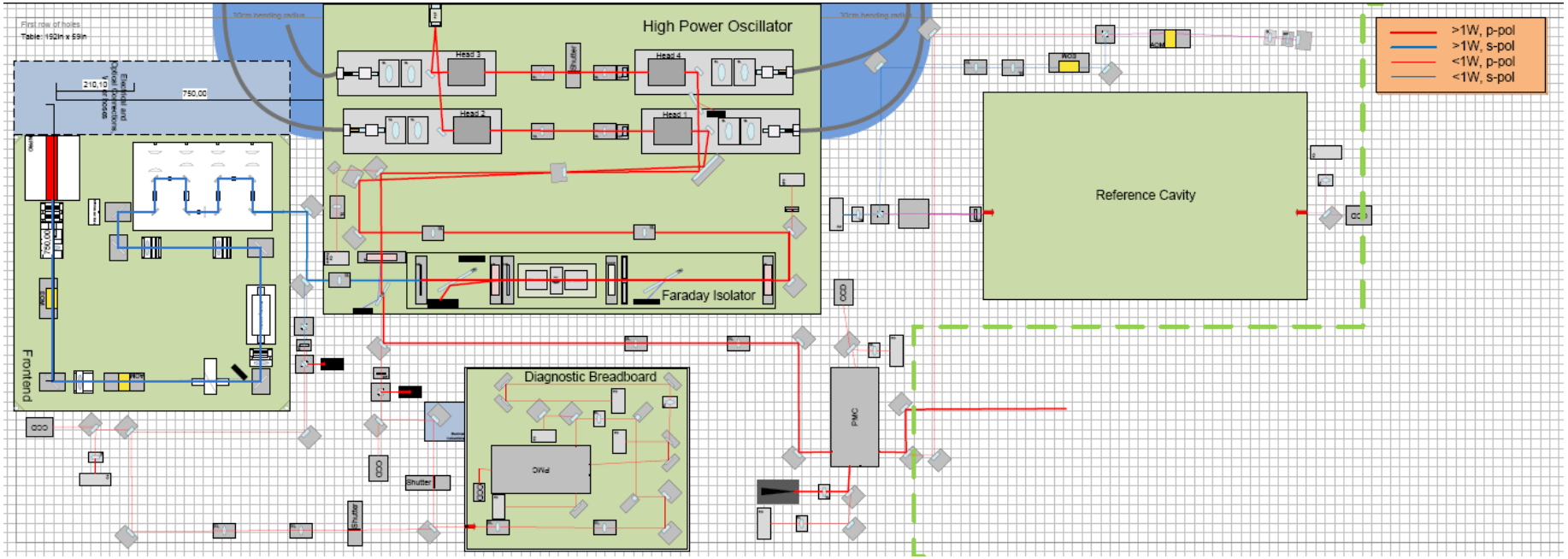


Figure 7 Diagram of AdvLIGO PSL.

The orange tilted box on the far left is the seed laser, which outputs a 2 Watt 1064 beam. The beam is immediately picked off at the noise eater for initial intensity stabilization. The beam then passes through and EOM and AOM to add sidebands and a Faraday isolator to stop any reflected beam. The beam is then sent through an amplifier stage that outputs 35 Watts and again is sent through a Faraday isolator. The beam is sent through another amplifier increasing the intensity to 200 Watts. After the high power amplifier, the beam passes through the PMC for spatial, pointing, and RF intensity stabilization. The beam is picked off after the PMC for the intensity stabilization and then is picked off again for the frequency stabilization. The beam then exits the PSL and enters a suspended modecleaner outside the PSL which provides stabilization. The actual layout of the PSL optics table is shown on the next page.

The frontend contains the 2 Watt seed laser and the first amplifier and outputs the 35 Watt beam. This beam is injected into the high power oscillator stage where it is amplified to 200 Watts. A small fraction (~300 mW) is also picked off and sent to the Diagnostic Breadboard. A small portion of the 200 Watt output (again ~300 mW) is also picked off and sent to the DBB. The output of the 200 Watt oscillator is sent through the PMC and (again ~300 mW) picked off and sent to the DBB (not shown in diagram). All optical paths not in the green boxes are installed, aligned, and modematched to the appropriate cavity.

Modematching is the process of shaping an input beam to an optical cavity. An optical cavity has a resonance condition such that the beam has a waist at a specific location and specific size. Thus, in order to obtain the maximum efficiency of an optical cavity, the input beam must not only be aligned properly, but the beam must also have a waste in the proper location and that waste must be the proper size. This is accomplished by placing lenses in front of the cavity in order to correctly shape the input beam. The location and focal length of the lenses are calculated using the JAMMT software. A screen shot is shown in Figure 8 following the PSL table layout. The waste and size of the beam to be shaped is input and begins at the left. Lenses with known focal lengths are entered and the position of the lenses are adjusted until the desired beam waste and position is obtained. Once this is done, the physical lenses must be installed and adjusted until the maximum power is transmitted through the cavity.


First row of holes
Table: 192in x 59in
High Power Oscillator
Head 3
Head 4
Head 2
Head 1
Shutter
Faraday Isolator
Reference Cavity
Frontend
Diagnostic Breadboard
PMC
Shutter
>1W, p-pol
>1W, s-pol
<1W, p-pol
<1W, s-pol

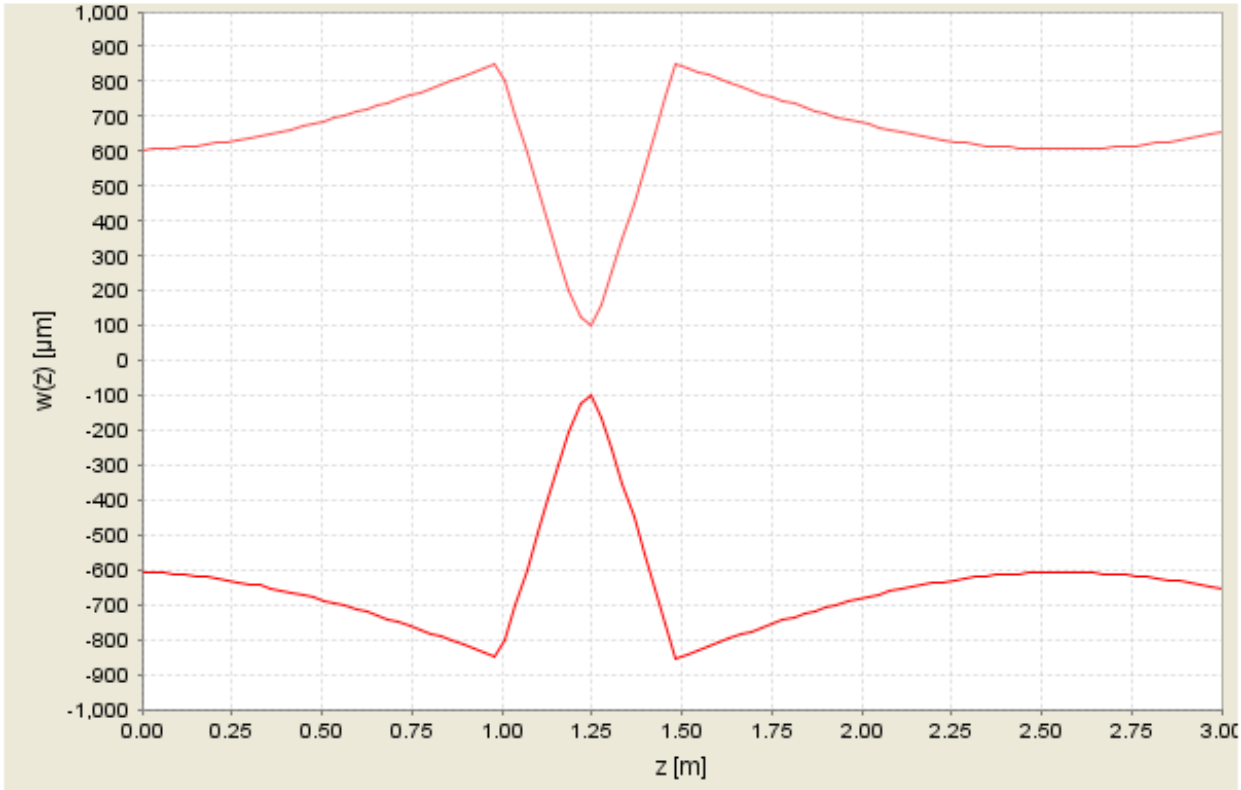


Figure 8 Screenshot of JAMMT modematching software.

Once all the optical paths are aligned and the cavities modematched, the Diagnostic Breadboard can then be used for characterization of different beams. The DBB measures five beam parameters: intensity noise, RF intensity noise, frequency noise, pointing noise, and spatial mode content. Both the intensity and RF intensity noise is measured simply with a photodiode that measures the intensity as a function of time. The time series is then used to compute the noise measurement. The pointing noise is measured with two quadrant photodiodes that measure the position of the beam as a function of time. The time series of the position of the beam is then converted to four pointing noise measurements as there are four degrees of freedom. The frequency noise is measured by holding the length of the modecleaner in the DBB constant and measuring the transmitted power as a function of time. Again the time series in converted to a frequency noise measurement. The mode quality is measured by varying the length of the cavity and measuring the transmitted power as a function of the length of the cavity. Since the length of the cavity determines which mode is resonant this data is then converted to spatial mode content.

Results

The Diagnostic Breadboard was used to compare beam parameters between the output of the 200 Watt oscillator and downstream of the PMC after the 200 Watt oscillator. The frequency and intensity loops were not yet installed. The data for the intensity noise is plotted in Figure 9 below.

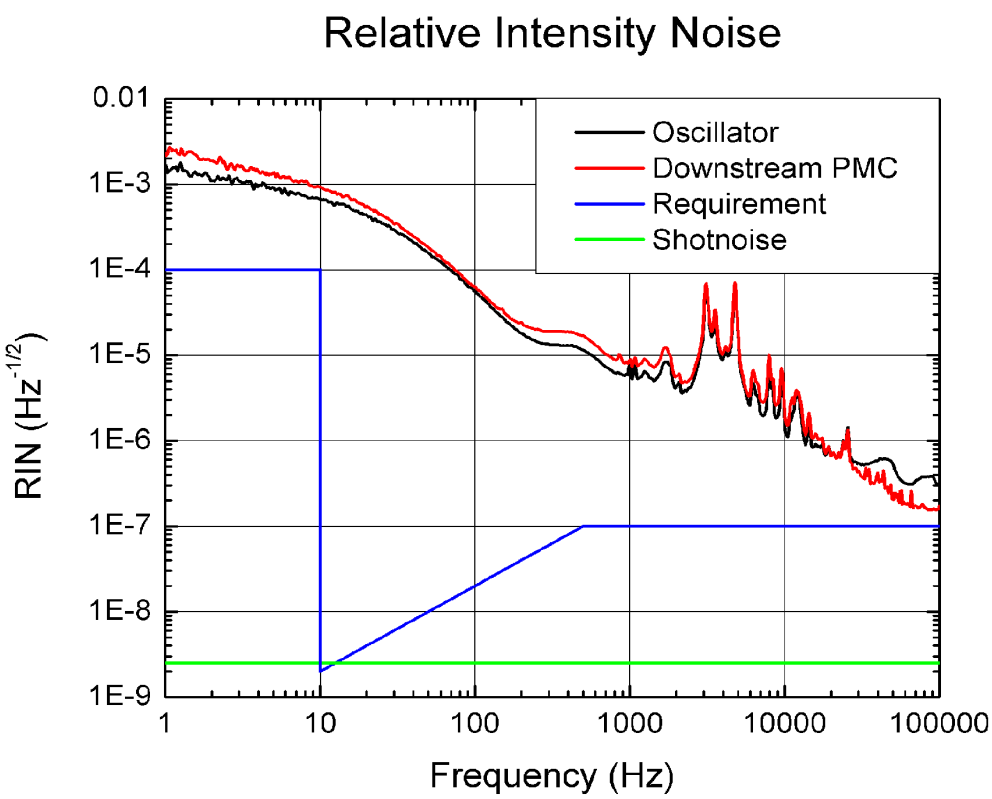


Figure 9 Relative intensity noise data.

The blue curve represents the AdvLIGO requirement and the green curve is the shot noise from the photodiode. The black curve represents the beam straight out of the 200 Watt oscillator and the red curve is the beam after it has passed through the PMC. The AdvLIGO requirement is most stringent at 10 Hz because this is where AdvLIGO expects to be the most sensitive. Though the data is far from the requirement level, the data is good as the intensity stabilization loop had not yet been installed. The intensity actually increased after the PMC but it is acceptable because it is less than a factor of 2 greater at all frequencies. Figure 10 shows the data for the intensity noise at radio frequencies. The color scheme is the same for this plot. Since the PMC filters out intensity fluctuations at RF, it is expected that the requirement is met. The beam downstream the PMC clearly has less RF intensity noise and is shot noise limited because it reaches a constant value somewhere between 5 and 10 MHz. Figure 11 shows the frequency noise data.

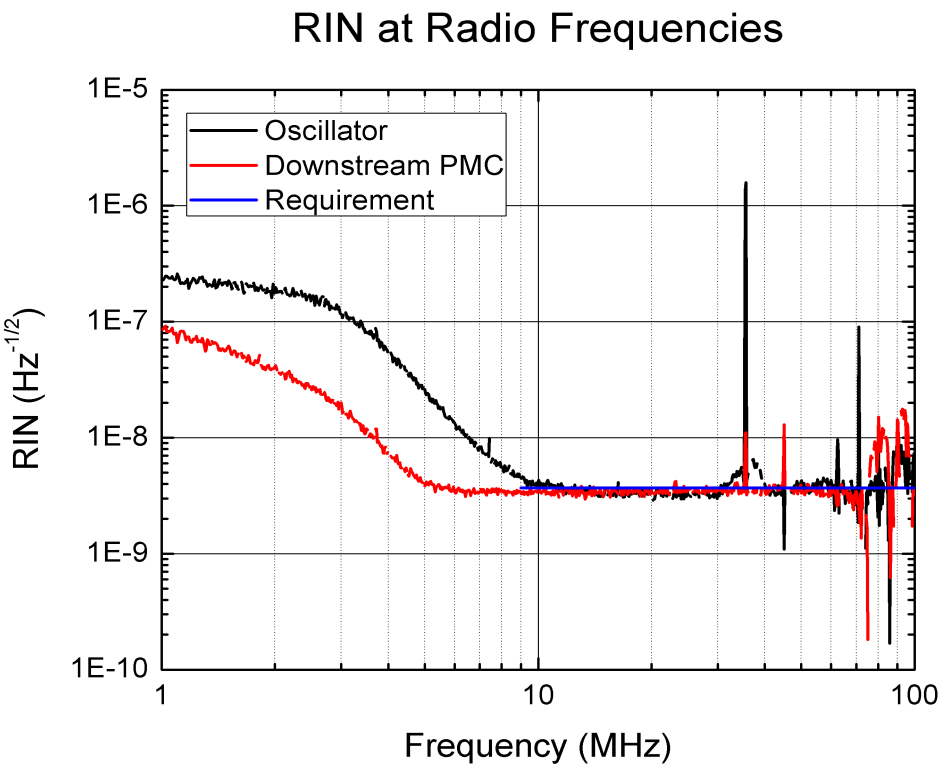


Figure 10 Relative intensity noise at radio frequencies.

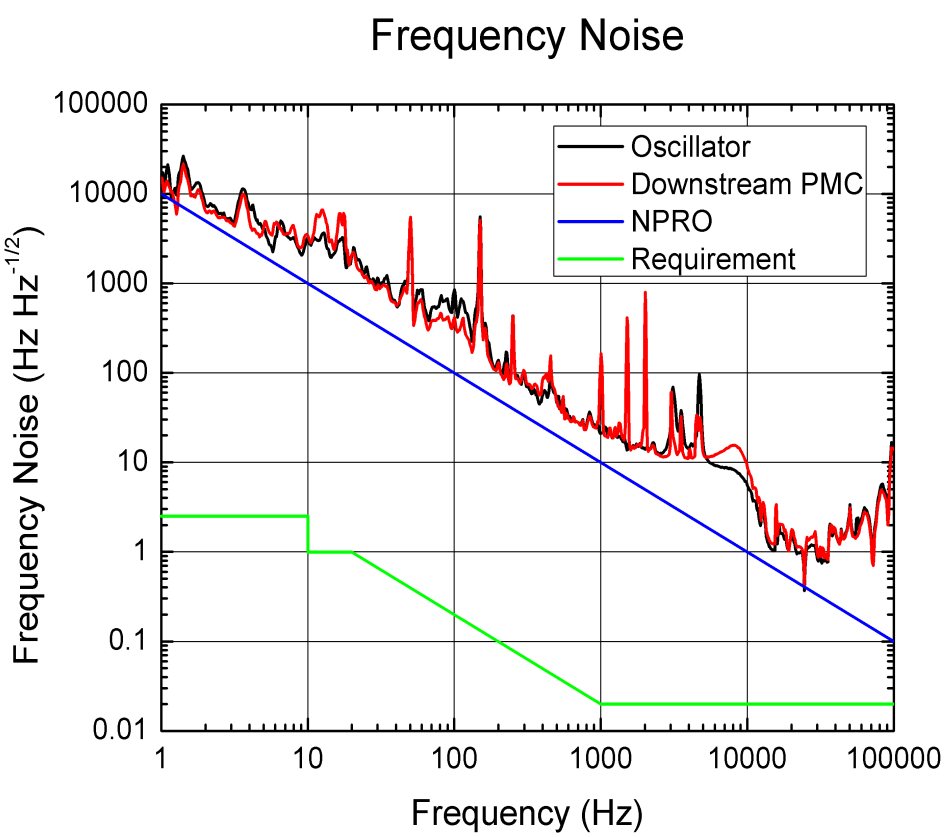


Figure 11 Frequency noise data.

In frequency noise plot, the green curve is the AdvLIGO requirement. The blue curve is an estimate of the frequency noise of the NPRO, which is the 2 Watt seed laser. The data clearly does not reach the AdvLIGO requirement but the frequency stabilization loop was not installed when the data was taken. It is expected, however, that the data should follow the estimate of the NPRO. The data is slightly above this curve and the cause is yet unknown. Figure 12 shows modescan data.

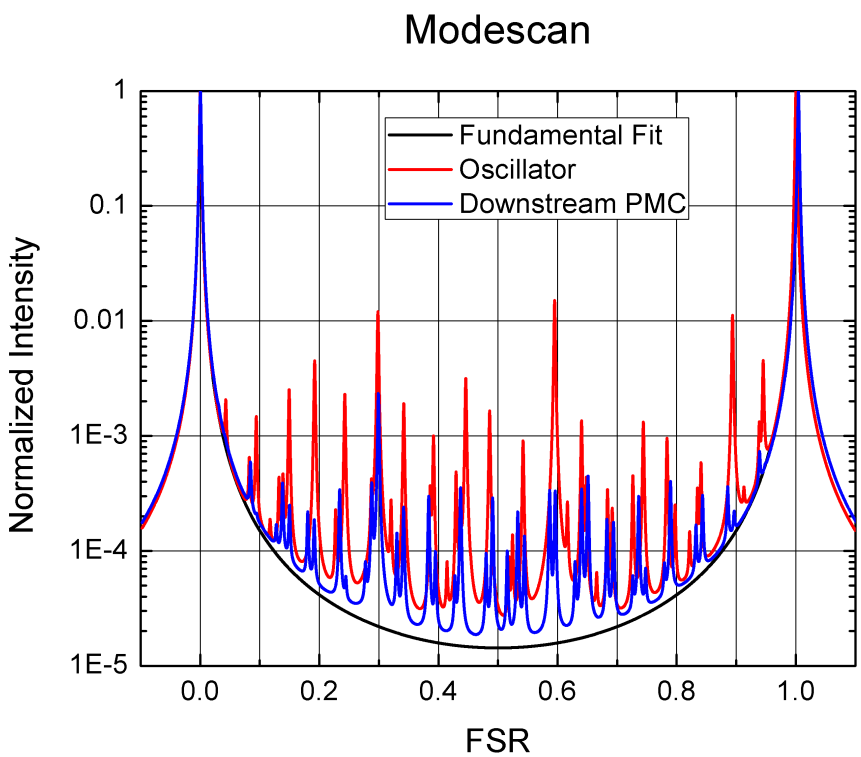


Figure 12 Modescan data.

In this plot, the black curve represents the fit of the fundamental Gaussian mode, the red curve is the modescan of the 200 Watt beam and the blue curve is the modescan of the beam after the PMC. The data clearly shows the PMC filters out most of the higher order modes. The red curve translates into ~7% higher order modes and the blue curve translates into ~1% higher order modes. Since AdvLIGO calls for less than 5% higher order modes, this requirement is easily met. Finally Figure 13 shows the pointing noise data. Again in these plots, the green curve represents the AdvLIGO requirement. In all four cases, the PMC significantly reduced the pointing noise as it should, but did not meet the requirement in most cases. This may not be a problem as there is a larger suspended modecleaner outside the PSL that would further reduce pointing noise.

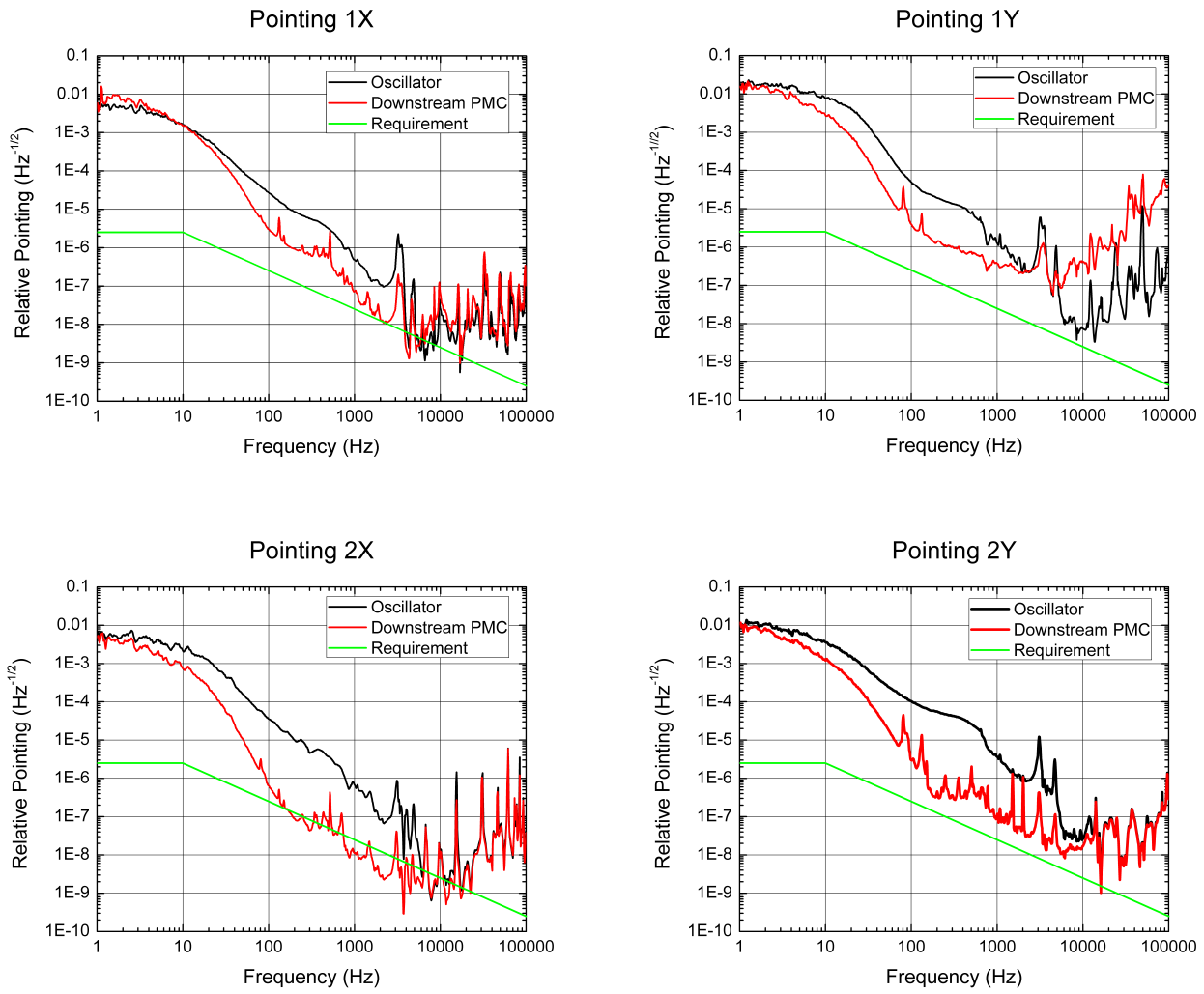


Figure 13 Pointing noise data.

Future Work

The next step in testing the AdvLIGO PSL is to install the frequency and intensity stabilization loops. Once these systems are installed, a full characterization of the beam downstream the PMC should be measured. This data should then be used to adjust the setup until AdvLIGO requirements are met or nearly met. When the requirements are met, long term stability testing can begin. LIGO must run for several years without need for a new PSL so long term testing is necessary. If long term testing succeeds, the AdvLIGO PSL can be installed at the LIGO sites and bring LIGO one step closer to detecting gravitational waves.