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- LIGO -
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2025 LIGO Final Report: Improvements to Sensitivity of Next Generation Detectors Through Internal Squeezing

Umran Serra Koca Mentored by Lee McCuller and Sander Vermeulen
California Institute of Technology

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

Massachusetts Institute of Technology
LIGO Project, Room NW17-161
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

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

1 Abstract

Current generation gravitational wave (GW) detectors such as LIGO/Virgo use frequency-dependent external squeezing incident on the dark port of the interferometer to improve sensitivity to strains [6]. Research has been done on internal squeezing, putting the squeezer within the IFO in the Signal Extraction Cavity (SEC). Internal squeezing can improve detection bandwidth and strain sensitivity at high frequencies while not impacting low frequency sensitivity [10]. However, no previous study has tried to implement directional internal squeezing. My project tests squeezing fields propagating toward the arms while anti squeezing field returning from the arms. I use the GW simulation package Finesse, with realistic loss values for injection and readout losses as well as a squeezer crystal with tunable, directional phases and amplitudes. I demonstrate that while internal squeezing does not provide a sensitivity improvement for Cosmic Explorer unless internal losses are less than 0.01%, this design could improve the sensitivity of LIGO above 1 kHz using internal losses on the order of .1%.

2 Background

Gravitational Waves are quadrupole waves, which means they stretch space in one direction while compressing it in the other. To detect these deformations in space time, interferometers such as the Laser Interferometer Gravitational Wave Observatory (LIGO) are used. LIGO detects gravitational waves by looking at the interference pattern from its 4 km arms as shown in Figure 1. If a gravitational wave is incident on the detector, light travels longer in one arm and shorter in the other. Thus, there is a differential phase which is then reflected as amplitude fluctuations due to interference at the output or dark port [6].

Gravitational waves are generated by some of the most energetic phenomena in the universe. Collisions between binary black hole, binary neutron star, and even black hole neutron star systems generate powerful ripples in space-time. However, unlike the immensity of these collisions, the length changes we detect are on the order of 10^{-19}m [1]. This means that the measurements are subject to quantum limits to uncertainty.

There are two main types of quantum noise that affect the sensitivity of current generation gravitational wave detectors: shot noise and Quantum Radiation Pressure Noise (QRPN). Shot noise refers to the uncertainty in the arrival times of photons that is encapsulated with Poisson statistics. Radiation pressure noise refers to the uncertainty in the phase of the light due to the movement of the mirrors as a result of radiation pressure force [6]. LIGO uses squeezed light to surpass limits to sensitivity due to these quantum noise sources.

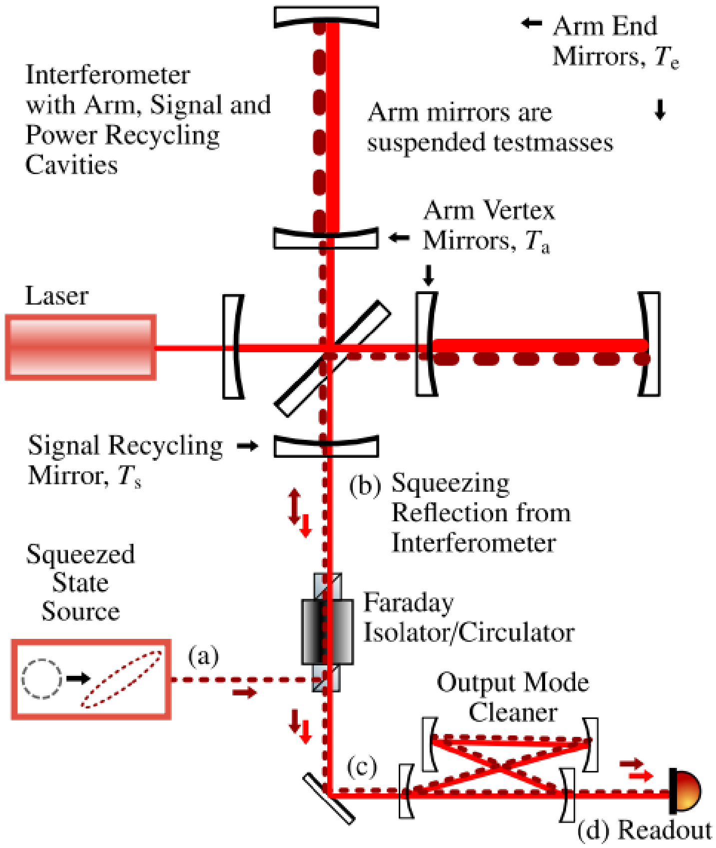

Figure 1: This is the advanced LIGO configuration. There are two arms with Fabry perot arm cavities. This is also called a dual recycled design because of the Power Recycling Mirror (PRM) and the Signal Recycling Mirror (SRM). I will refer to the SRM as the Signal Extraction Mirror (SEM) throughout this report since this is the mode it is used in currently [11].

2.1 Squeezed Light

Squeezed states are non classical states of light. To understand what this means, it is instructive to start with representations of electric fields in terms of quadrature operators. For a monochromatic field, a field in which there is only one frequency component, the electric field can be written as:

$$\hat{E}(t) = \hat{X}\cos(\omega t) + \hat{Y}\sin(\omega t) \tag{1}$$

Here, $\hat{X}$ represents the amplitude quadrature operator and $\hat{Y}$ represents the phase quadrature operator. ω is the frequency of the field. $\hat{X}$ and $\hat{Y}$ are non-commuting Hermitian operators. This means they are observables that are related to one another with an uncertainty relationship. In this case:

$$\Delta^2\hat{X}\Delta^2\hat{Y} \geq \frac{1}{16} \tag{2}$$

With this uncertainty relationship in mind, it is convenient to represent fields in quantum optics using phase space diagrams. The area of the ball has to be greater than or equal to the uncertainty product of the two quadrature operators. The stick refers to the amplitude of the field. Fields with zero amplitude are vacuum fields. Fields with nonzero amplitudes and equal uncertainty in both quadratures, represented by the width of the uncertainty ellipse in either direction, are coherent fields. Coherent fields represent laser light [13].

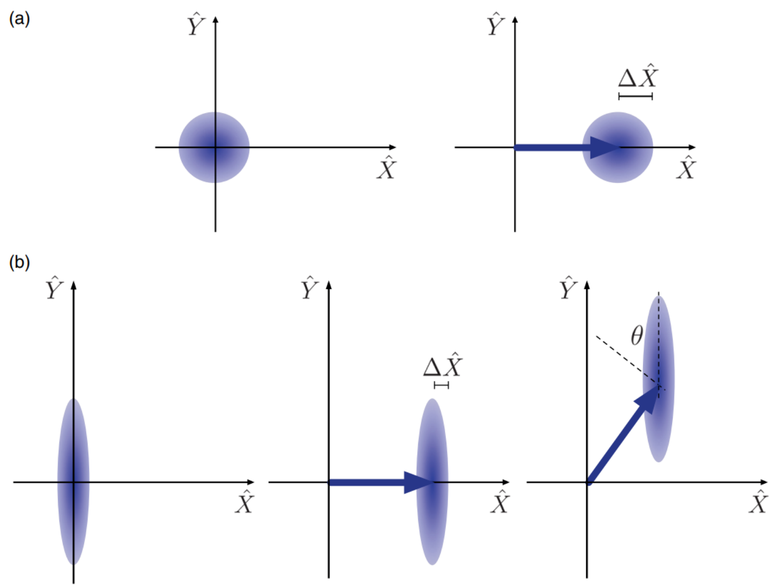

Figure 2: a) represents a vacuum field on the left and a displaced vacuum field or a coherent field on the right. b) represents a squeezed vacuum field on the left, a displaced squeezed vacuum field in the middle, and a displaced vacuum field squeezed at an angle of θ to the right [5].

When a field is squeezed in the amplitude quadrature, the uncertainty in the amplitude is reduced but the uncertainty in the phase is increased, preserving the uncertainty product. The squeezing operation can be described by the two photon formalism, the mathematical description used in quantum optics, with matrices acting on the quadrature operators.

$$S(r,\theta) = \begin{bmatrix} \cosh(r) - \sinh(r)\cos(2\theta) & -\sinh(r)\sin(2\theta) \\ -\sinh(r)\sin(2\theta) & \cosh(r) + \sinh(r)\cos(2\theta) \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \hat{X}_{sq} \\ \hat{Y}_{sq} \end{bmatrix} = S(r,\theta) \begin{bmatrix} \hat{X} \\ \hat{Y} \end{bmatrix} \tag{4}$$

[5]

The reason LIGO uses squeezed light is to obtain a better Signal to Noise Ratio (SNR) when detecting gravitational waves. Squeezed vacuum states are injected from the output port or the dark port of the interferometer. These states are squeezed so that they have reduced uncertainty in the amplitude quadrature for lower frequencies and reduced uncertainty in the phase quadrature for higher frequencies. This way they account for QRPN and shot noise. Using squeezed light, LIGO can improve its sensitivity below the Standard Quantum Limit: this is total quantum noise when QRPN and shot noise are treated as uncorrelated.

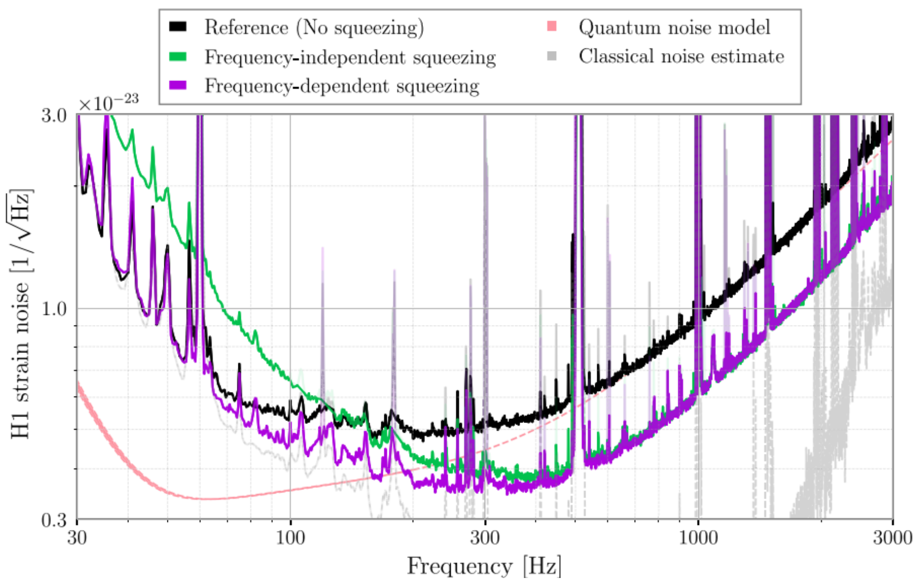

Figure 3: This is a sensitivity curve for LIGO Hanford, describing how sensitive the detector is to signals at various frequencies. The lower the curve, the better the sensitivity. Frequency dependent squeezing is responsible for the improvement from the black curve to the purple curve [7].

Because squeezed states are produced outside of the interferometer and injected from the dark port, this is called external squeezing. Research has been done into new squeezing configurations, called internal squeezing. Internal squeezing refers to putting a nonlinear crystal inside the Signal Extraction Cavity (SEC). This is the cavity formed by the Signal Extraction Mirror (SEM) and the input mirrors.

2.2 Internal Squeezing and Quantum Expander

Current generation detectors use cavities in the arms as well as the SEC on the dark port of the detector. Resonators lower the Quantum Cramer Rao Bound (QCRB). This bound represents the theoretical limit to detector sensitivity accounting for quantum noise. However, resonators only lower QCRB at frequencies below their linewidth, limiting the detection bandwidth. External squeezing cannot improve this reduction in bandwidth, but internal squeezing can. With a nonlinear crystal inside the SEC, quantum uncertainty at high frequencies gets squeezed such that it compensates the reduction in signal enhancement due to cavity linewidth. This new technique can scale the noise in the same way as the signal is reduced, boosting the SNR at high frequencies [10].

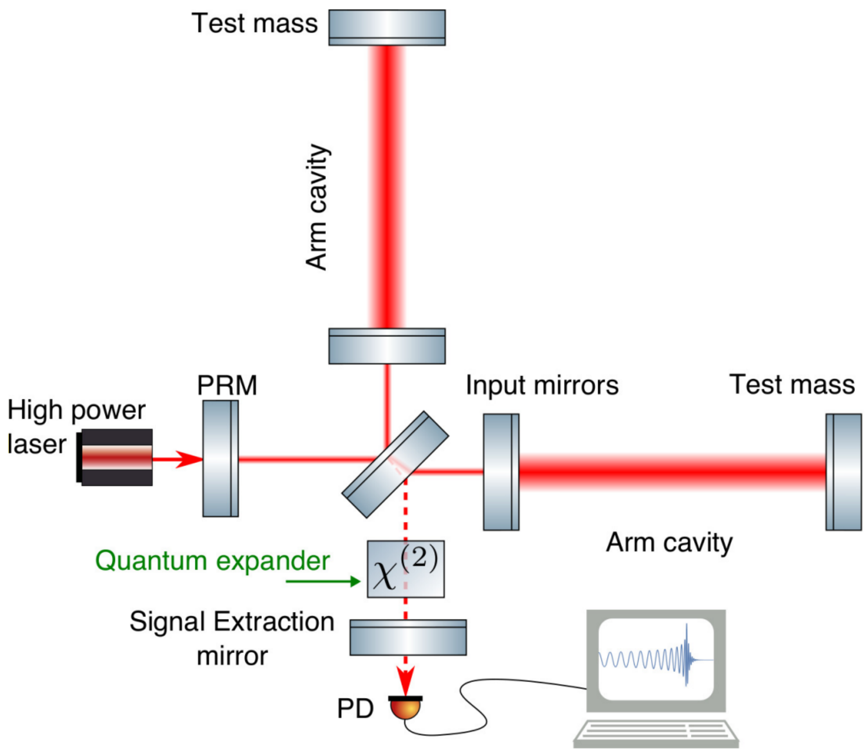

Figure 4: The nonlinear crystal dubbed the quantum expander is put within the SEC as shown here. While it is not shown here, this design is compatible with external squeezing. Realistically, Quantum expander and external squeezing would be employed in conjunction.

The overall effect of the quantum expander is to expand the photon shot noise limited bandwidth of the detector at high frequencies. It leaves the low frequency sensitivity unchanged since frequencies around the resonance of the arm cavities (which is the same frequency of the carrier) do not correspond to SEC resonances. The SEC is resonant at higher frequencies [10]. This means that the internal squeezing effect is present at these higher frequencies. Unfortunately, like all optical systems, adding a squeezer inside the SEC suffers from quantum decoherence in the form of optical loss.

It is necessary to account for internal, injection, and readout losses when assessing the sensitivity of a gravitational wave detector. Readout losses and internal losses can significantly degrade the sensitivity improvement from internal squeezing. This motivates my research this summer.

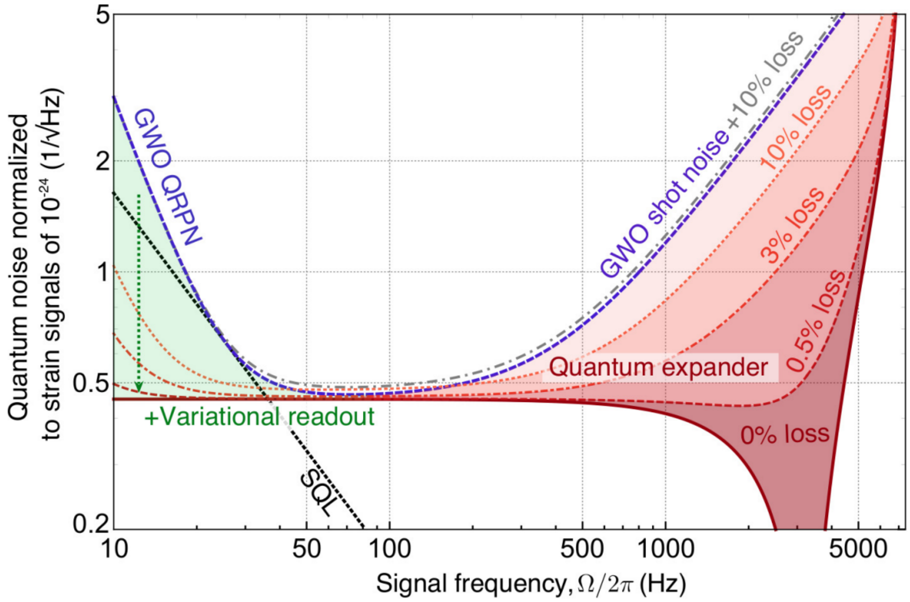

Figure 5: Here, the effect of various readout losses is shown on the sensitivity of the Quantum Expander setup. With more readout loss, the more the high frequency sensitivity is degraded. Current generation detectors like LIGO use 10% readout loss, but for future generation detectors like Cosmic Explorer, this value is projected to be around 5%. To generate this sensitivity curve parametrs of 3rd generation observatories were used: 1550 nm wavelength, 4Mw of power in the arm cavities, 20 km arms, 56 m SEC, 200 kg mirror mass, input transmission of 0.07, and SEM transmission of 0.35 [10].

2.3 Objective

Minimizing the sensitivity reduction due to readout losses is an important research question in gravitational wave science. Further, conventional internal squeezing, as in squeezing for both the field going into the arms and the field coming out of it, reduces the signal as well as the noise. With these challenges in mind, squeezing the field going into the arms and anti squeezing the field coming out of the arms could improve high frequency sensitivity even more. This is the setup I examined this summer. My goal was to quantify the improvements to next generation and current generation gravitational wave detectors using internal squeezing and anti squeezing in a setup that I will refer to as bidirectional squeezing. This scheme is shown in Figure 6. The field is squeezed at point B and anti squeezed at point D where the signal arrow and noise ellipse are both elongated along the vertical axis.

Anti squeezing at point D ”locks in” a good Signal to Noise ratio before incurring readout loss. If we consider losses to be unsqueezed vacuum states that are mixed with the noise ellipse from point D, further degradation of the squeezing is limited since the uncertainty can only be increased to the level of unsqueezed vacuum through such loss. Thus, not only do we enlarge the signal, but we also minimize the effect of readout loss.

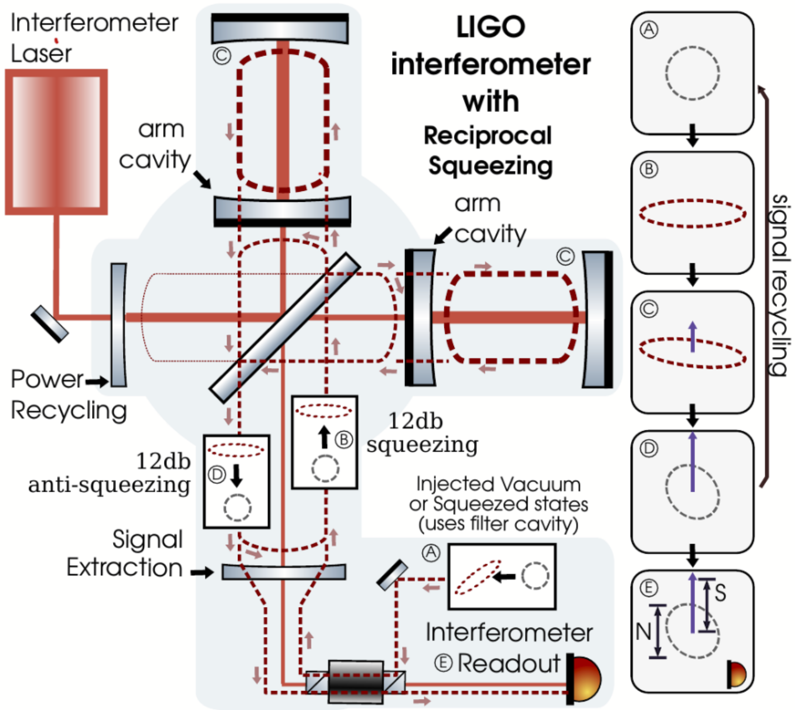

Figure 6: The field going into the arms is squeezed, compressing the noise ellipse and the signal along the phase quadrature while the field coming out of the arms is anti squeezed, expanding the noise ellipse and the signal along the phase quadrature.

3 Results

To investigate the sensitivity with this setup, I used a python package called Finesse. The setup is explained in detail in the methods section. I first implemented bidirectional squeezing in Cosmic Explorer with a new directional squeezer crystal element. I also added input, output, and internal losses. Input and output losses were matched with the Gravitational Wave Interferometer Noise Calculator's (GWINC) Cosmic Explorer model injection and readout losses. The sensitivity curve was generated for various internal losses.

As shown in Figure 7, for very small internal losses, close to 0, the sensitivity is improved. However, for more realistic internal losses on the order of 0.001 and above, it is not possible to beat the Cosmic Explorer sensitivity curve unlike what we had hoped when we started this project. The reason why internal losses have a big effect on Cosmic Explorer is the same reason why squeezing inside cavities is amplified greatly. Inside the Signal Extraction Cavity, especially on resonance, the field takes multiple round trips. The number of round trips increases with the finesse of the cavity. Keeping everything else the same, Cosmic Explorer can be thought of as a LIGO model with longer arms and smaller transmission on the SEM. A smaller SEM transmission increases the finesse greatly, meaning that internal losses have a more drastic effect on the sensitivity. This also means that while reciprocal internal squeezing was not successful in improving high frequency sensitivity for Cosmic Explorer, it

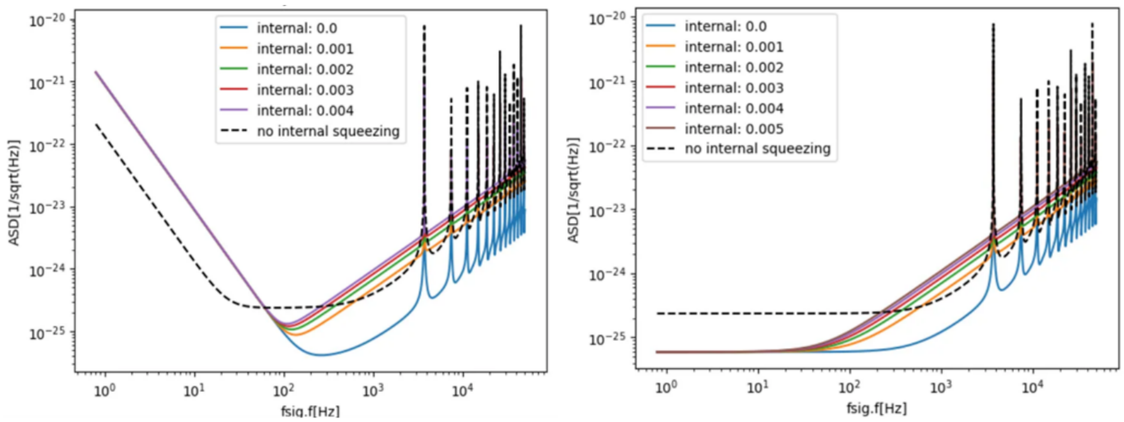

Figure 7: The plot on the left incorporates the effect of radiation pressure. The plot on the right does not allow the masses to move. My Cosmic Explorer model uses 12 dB of external squeezing, 2.5% input loss and 5% output loss. The internal squeezing parameters used for the Cosmic Explorer model are z = 1.9 for squeezing and z = 1.90001 for anti squeezing

might be successful in doing so for LIGO.

	LIGO	**Cosmic Explorer**
SEM Transmission	0.325	0.014
Arm Length	4 km	40 km
Laser Power	125 W	165 W

Table 1: Comparison of parameters between LIGO and Cosmic Explorer [3].

I implemented the same setup on FINESSE for LIGO, using LIGO appropriate laser power, mirror transmissions, and arm lengths.

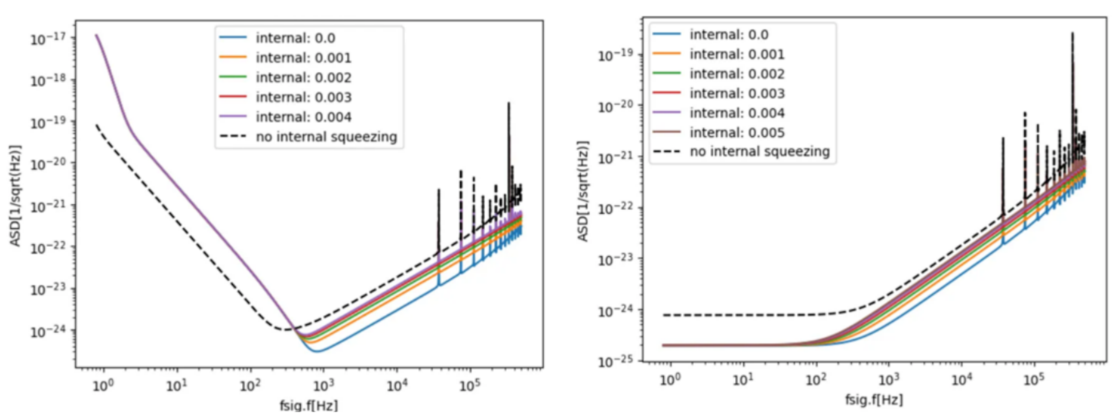

Figure 8: The plot on the left incorporates the effect of radiation pressure. The plot on the right does not allow the masses to move. My LIGO model uses 12 dB of external squeezing, 5% input loss and 10% output loss. The internal squeezing parameters used for the LIGO model are z = 1.9 for squeezing and z = 1.90001 for anti squeezing

For LIGO, it is possible to improve the sensitivity using reciprocal internal squeezing as shown in Figure 8. With losses on the order of 0.001, the sensitivity curve at higher frequencies, above 100 Hz, is greatly improved. High frequency sensitivity is crucial for LIGO's science goals. For instance, binary neutron star mergers are detected at frequencies around kHz frequencies [4]. Thus, bidirectional squeezing , if implemented, could greatly aid in LIGO's science goals.

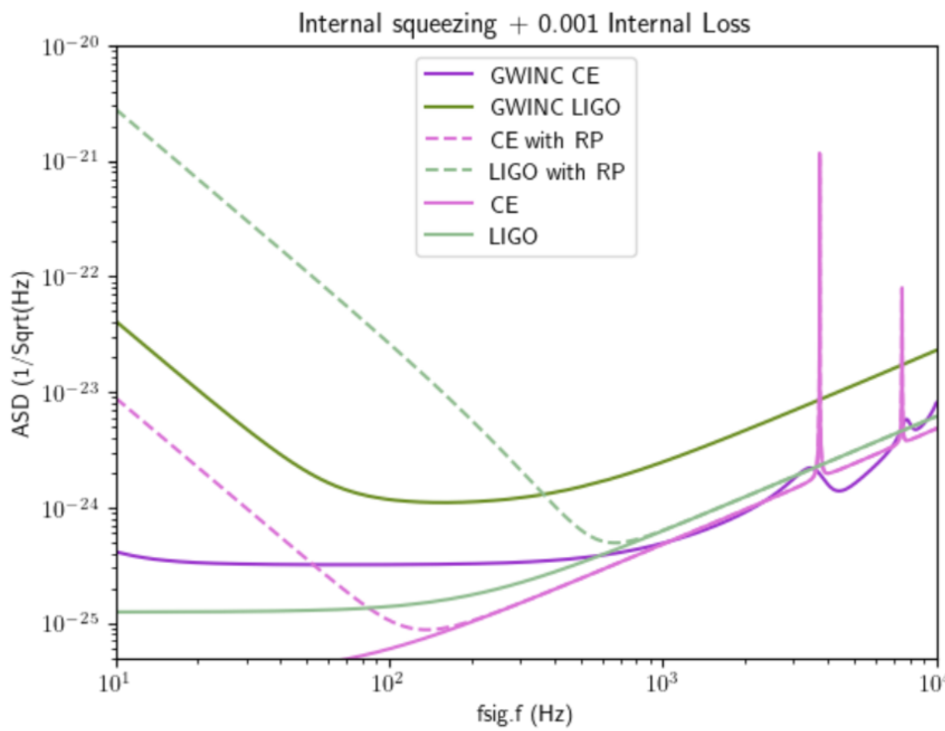

Figure 9: Comparison of Cosmic Explorer and LIGO sensitivity curves with and without radiation pressure. The GWINC models do not use frequency dependent squeezing. The sensitivity curves were generated with LIGO and Cosmic Explorer specific injection and readout losses, but internal loss is fixed at 0.001 for both LIGO and CE models. External squeezing of 12 dB is used for both models. Reciprocal internal squeezing of $z_{net} = 0.0001$ is used. It can be seen, again, that bidirectional squeezing improves the sensitivity for LIGO at high frequencies but not for Cosmic Explorer when compared to the GWINC curve.

3.1 Implications of Radiation Pressure

For both Cosmic Explorer and LIGO models, the low frequency sensitivity was adversely affected by the presence of bidirectional squeezing . This is because bidirectional squeezing in combination with radiation pressure degrades the sensitivity. Bidirectional squeezing enhances amplitude quadrature uncertainty for light entering the AS port which produces radiation pressure fluctuations. These radiation pressure fluctuations are converted to phase quadrature uncertainty by the mirrors which is then anti squeezed upon exiting the SEC. This gives us overall worse sensitivity compared to the case without bidirectional squeezing.

4 Methods

4.1 Directional Squeezer Crystal

At the start of this project, FINESSE did not have a component that could squeeze non vacuum fields. Dr. Kevin Kuns from the Massachusetts Institute of Technology wrote the code for a squeezer crystal able to squeeze any field using the two photon formalism and Bogoliubov matrices as described in the background section. FINESSE converts between sidebands and cosine and sine (amplitude and phase) quadratures as shown below:

$$A = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -i & i \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \hat{X} \\ \hat{Y} \end{bmatrix} = A \begin{bmatrix} a_+ \\ a_-^\dagger \end{bmatrix} \tag{6}$$

$a_+(\omega) = a(\omega_0 + \omega)$ represents the upper sideband around the carrier. $a_-^\dagger(\omega) = a(\omega_0 - \omega)$ represents the conjugate of the lower sideband. These are both operators [2].

I modified Dr. Kuns' code to make the squeezer crystal directional. Originally, it would take in 1 squeezing parameter and squeeze in both directions in the same way. I added two more parameters to the constructor of the squeezer crystal object, making a total of 4 parameters: z_f, ϕ_f, z_b, ϕ_b. Here, the subscript f corresponds to the squeezing from port 1 to port 2, keeping with FINESSE convention. The subscript b corresponds to the action of squeezing on the field going from port 2 to port 1.

Squeezing inside a cavity is amplified. The net bidirectional squeezing can be calculated using the following formula:

$$Z = \log(\frac{e^{z_{net}} - r_1}{1 - r_1 e^{z_{net}}}) \quad (7)$$

[8]

Here, $z_{net} = z_f - z_b$. Thus, for very small values of z_{net}, we can get very large effective squeezing. This also raises a concern, for what values of z_{net} do we start lasing? Lasing is defined as generating and amplifying monochromatic coherent light. Lasing, in this case, means the generation of bright sidebands. Above $z_{net} >$ SEM, the upper and lower sidebands get amplified through parametric down conversion in the SEC on each roundtrip more than they get balanced by the losses [12].

4.2 Losses and Squeezing Level

4.2.1 Losses

The types of losses I accounted for in my FINESSE model were input, internal, and output losses. Input losses are what are called injection losses in GWINC, and output losses are referred to as readout losses in GWINC. The way I modeled loss is by using a beam splitter in FINESSE that would transmit a fraction of the power. A squeezed field with or without a signal is mixed with an unsqueezed vacuum field at the beamp splitter. The result is combining a pure state with another pure state to make a mixed state. The way to represent this using a phase space diagram is:

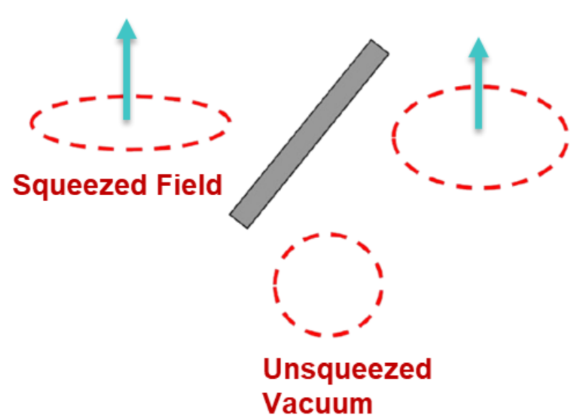

Figure 10: Beamsplutter model of loss

The combined model with the squeezer crystal and losses can be represented using the following diagram:

We can look at the effect of various losses on the sensitivity individually to make sense of their combined impact.

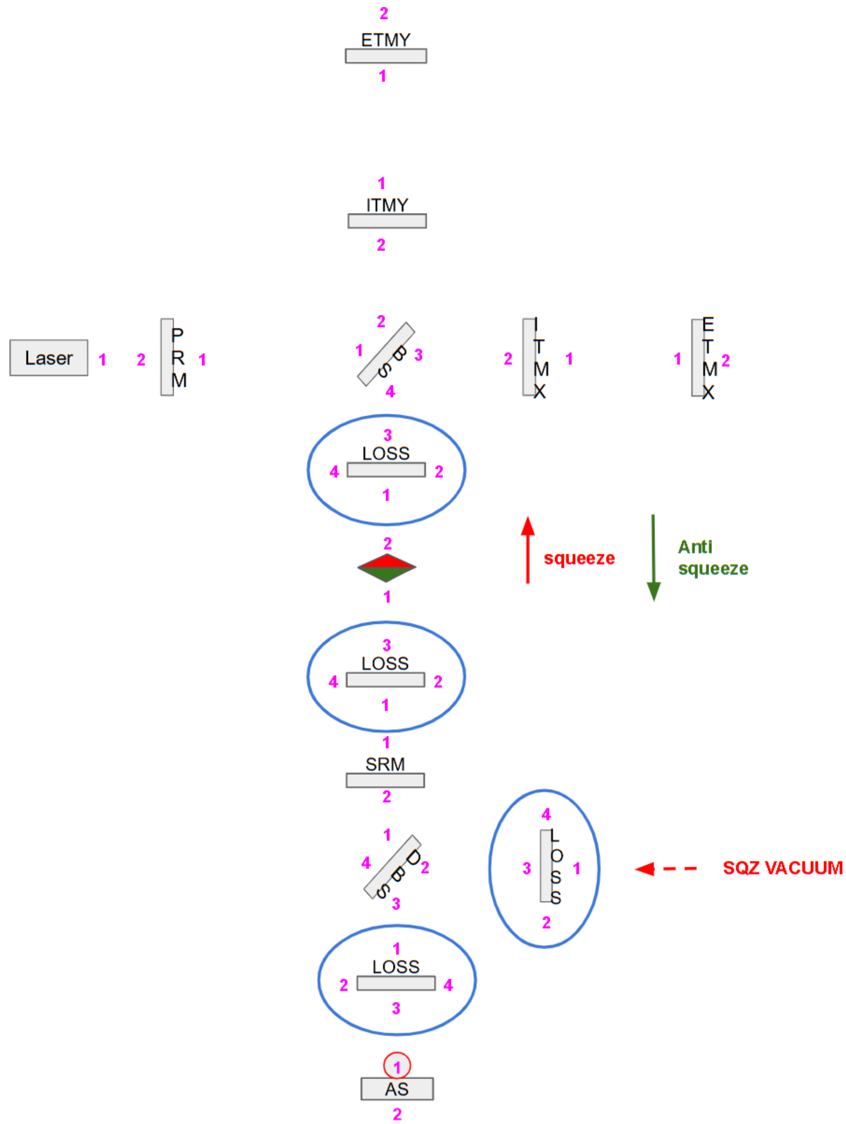

Figure 11: The losses are circled here. The loss after the unsqueezed vacuum is the input loss. The losses directly before and after the squeezer crystal are internal losses. When I set an internal loss value, I am setting the loss the same for both of these beam splitters. The output loss is before the readout which is at port 1 of the DC Readout Component labeled AS.

With internal loss, we can see that the sensitivity starts to worsen around 10 Hz as shown in Figure 12. The reduction in sensitivity is significant, underscoring the resonance-enhanced effect of losses within the cavity.

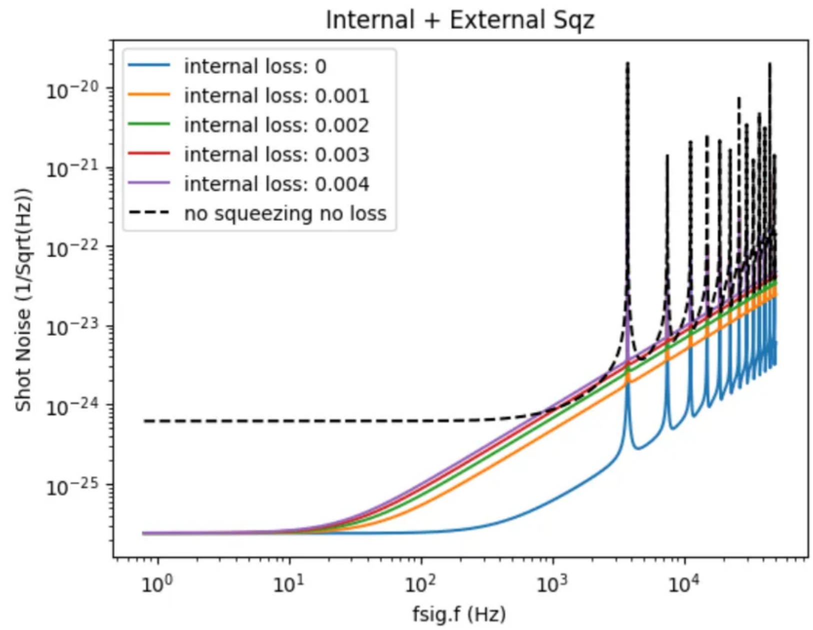

Figure 12: External squeezing is kept at 12 dB. There is no input or output loss. The internal loss is varied and the sensitivity is modeled.

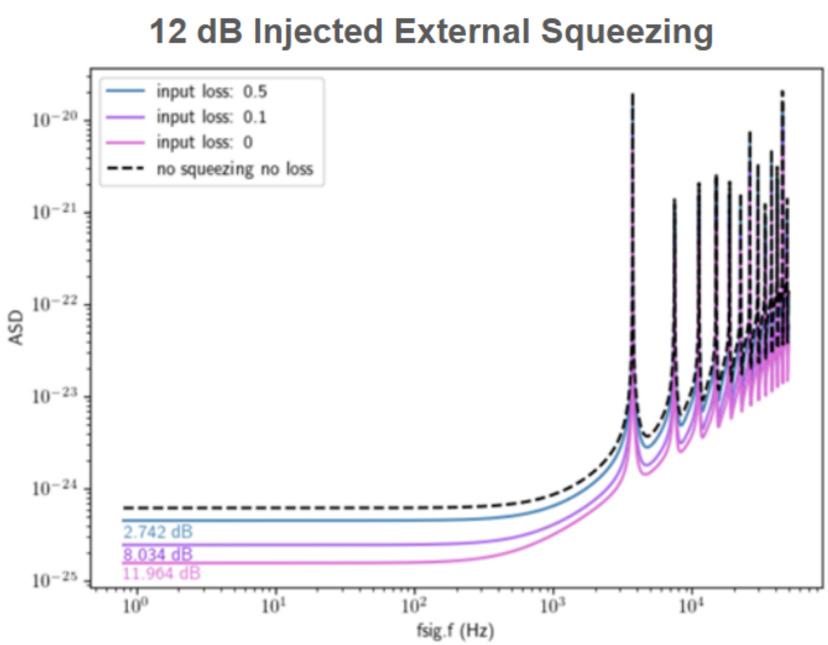

Figure 13: There is 0 internal squeezing present for this figure. The level of input loss is varied and the resulting effective external squeezing is displayed.

Since input losses are outside of the interferometer, they only affect external squeezing. This effect can be described as reducing the strength of external squeezing or rather shifting the sensitivity curve up at all frequencies. For a model with only internal squeezing, input losses do not have any effect on the sensitivity.

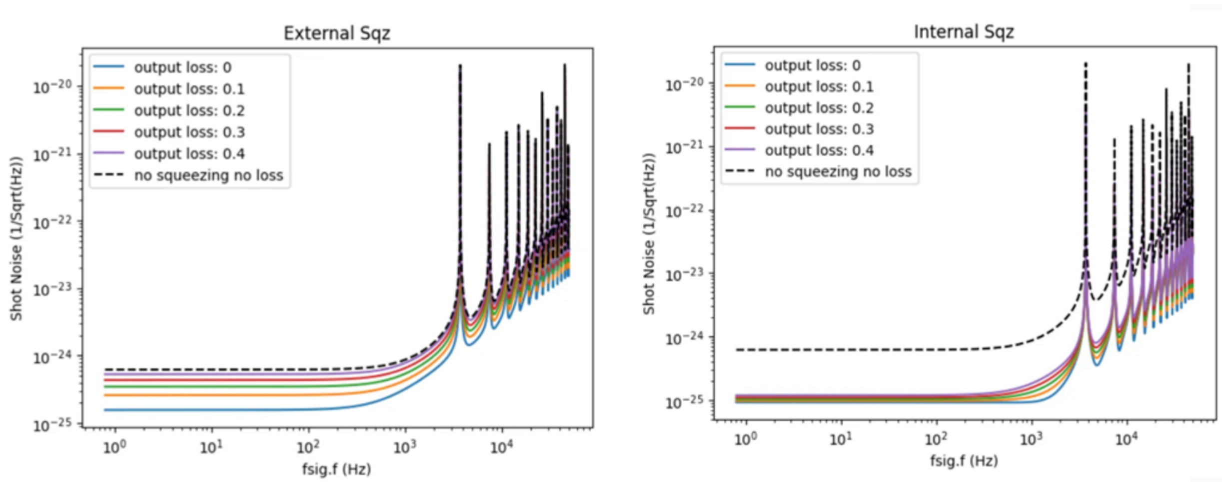

Figure 14: Output loss is the only loss present in this figure. There is 12 dB of external squeezing in the Figure titled external squeezing. This model has no internal squeezing There is 12 dB of net bidirectional squeezing in the Figure titled internal squeezing. This model does not have external squeezing.

For output losses, we can see that they affect both external squeezing and internal squeezing. Inputting the same decibel value of squeezing, squeezing inside the SEC is more resistant to output losses compared to external squeezing. However, the internal and external sensitivity curves match up at SEC resonances given the same decibel squeezing and the same output loss.

4.2.2 Squeezing Level

For the overall model, I chose the level of internal squeezing and internal anti squeezing of the squeezer crystal so that I would get the best possible sensitivity curve. I found that this was when z_f and z_b were the same. However, when the anti squeezing and squeezing level were set to the same value, the sensitivity curve exhibited a lot of noise. To work around this problem, I set the values for z_f and z_b offset by 0.00001. This was a large enough difference that I could avoid the noise while getting the best possible sensitivity.

The internal squeezing and anti squeezing levels were adjusted for optimal sensitivity keeping 12 dB of external squeezing fixed. Setting the anti squeezing level equal to the squeezing level effectively cancels out internal squeezing but still gives a sensitivity improvement on top of external squeezing. Another configuration of interest was to balance all of the squeezing, including external squeezing, with anti squeezing.

$$Z + z_{ext} = 0 \tag{8}$$

Here, Z is the net bidirectional squeezing in dB adjusted for losses and z_{ext} is the net external squeezing in dB adjusted for losses. The conversion from squeezing amplitude to dB is given in equation 9.

$$dB = z \cdot log_{10}(e) \cdot 20 \tag{9}$$

$$Z = \frac{\log\left(\frac{e^{z_{net}} - \sqrt{1-T-L}}{1-\frac{1}{2}\sqrt{1-T-L}\, e^{z_{net}}}\right)}{\log(e)} \qquad z_{ext} \quad = \frac{-10\log\left((1-l)\cdot 10^{-dB/10} + l\right)}{20\log(e)} \tag{10}$$

[9]

In equation 10, T represents the power transmission of the SEM. L represents the power loss of the SEM. l represents the input power loss.

Canceling out the total squeezing (external + bidirectional squeezing) restores the noise ellipse back to the unsqueezed vacuum level. This means that when the field picks up readout losses, the result is combining an unsqueezed vacuum ellipse with another unsqueezed vacuum ellipse which has no effect on the noise. This effectively makes the field immune to readout losses. Unfortunately, the resulting sensitivity curve matched up closely with the curve from setting z_f and z_b the same, giving no discernible improvement.

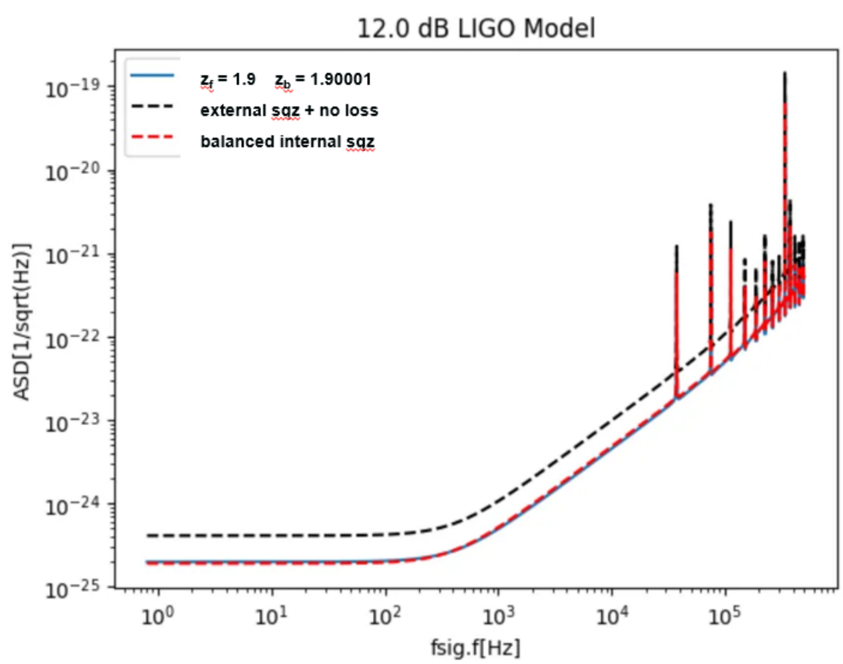

Figure 15: Here, overall 0 net squeezing is given in red and the 0 bidirectional squeezing is given in blue. For both models, 12 dB of external squeezing is used but for the red model, the internal squeezing is adjusted so that it cancels out all of the external squeezing. The no loss curve only includes external squeezing, and serves as a comparison point.

5 Acknowledgments

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