LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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# Optical Enhancement Cavity Project Interim Report 1

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# 1 Introduction

The Laser Interferometer Gravitational-wave Observatory (LIGO), utilizes long baseline Michelson interferometers to detect gravitational waves (GWs) generated by astronomical events like black hole mergers or neutron star collisions. As GWs pass through each detector, they warp space-time, changing the path-length difference of the Michelson interferometers leading to a detectable signal. In order to enhance this signal, LIGO makes use of Fabry-Perot cavities to increase the power within each arm of the interferometer. This increased power enhances the modulation GWs cause, increasing the sensitivity of the detector [1]. This principle of utilizing optical cavities to build up high amounts of optical power has broad applications across physics, including in laser inertial confinement fusion.

Blue Laser Fusion (BLF) is working to establish the world's first inertial fusion energy (IFE) generation. BLF utilizes Coherent Beam Combining (CBC) technology and an Optical Enhancement Cavity (OEC) to produce a highly efficient pulsed laser system capable of producing 10 kJ pulses at repetition rates of 1 to 10 Hz. Through the combination of 500 of these systems, BLF aims to generate 5 MJ pulses at high repetition rates for fusion ignition [2].

The focus of this project will be on the OEC. An OEC is a Fabry-Perot optical cavity capable of building up and storing high intracavity powers. Past work on the OEC has achieved enhancement of a continuous wave (CW) laser beam by a factor of 58,461, achieving circulating powers of several kW within a 1.5 m demonstration cavity [3]. A key next step for the OEC, however, is achieving locking to the OEC with the laser operating in pulsed mode. Pulsed operation of the OEC allows for high peak powers required for inertial fusion, but introduces significant challenges.

This project aims to demonstrate pulse-locking of our laser to the OEC and to understand the technical challenges of locking pulses to a high finesse optical cavity. The techniques utilized can be adapted to 15 m and 150 m enhancement cavities currently in development at BLF for the purpose of fusion.

# 2 Background

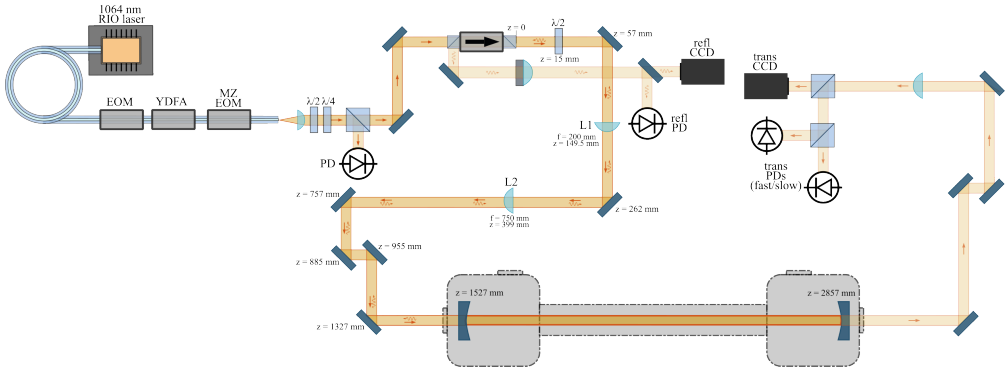



Figure 1: Schematic of current OEC setup. Figure credit: Georgia Bolingbroke

The OEC is a standard Fabry-Perot optical cavity consisting of two highly reflective mirrors. Light directed into the cavity that satisfies the resonant condition

$$n\lambda = 2L \tag{1}$$

where $\lambda$ is the wavelength of incident light, L is the length of the cavity, and n is an integer, builds up over time as the accumulated phase of circulating light matches new incident light, constructively interfering.

Related to this resonance condition is the free spectral range (FSR) of the cavity, which is a measure of the distance between resonant peaks of the cavity in the frequency domain. By substituting $c/f = \lambda$ into Eq. 1, we see that the distance between resonant peaks is given by

$$FSR = \frac{nc}{2L} \tag{2}$$

with resonant peaks contained at an integer multiple of the FSR.

A measure of how well light is stored in the cavity is called the finesse, measuring the average number of times a photon circulates before it exits the cavity. The OEC is a cavity with ultra-high finesse, with mirror losses of only 3.4 parts-per-million (ppm). This ultra-high reflectivity yields a theoretical finesse given by

$$Finesse \approx \frac{\pi(R_1R_2)^{1/4}}{1-(R_1R_2)^{1/2}} \tag{3}$$

where R is the reflectivity of the mirrors. If the losses in our cavity are only derived from transmission through the mirrors, the theoretical finesse of the OEC is approximately 924,000. In practice, the finesse will be lower than this value as intracavity losses occur due to stray dust and imperfect alignment.

To minimize these losses, the OEC is contained within an ultra-high-vacuum (UHV) chamber reaching pressures of $10^{-9}$ torr. Prior to this project, significant work with the OEC has already been completed as summarized in Ref. [3]. Through this work, the OEC achieved a finesse of 419,000.

The FSR and finesse of the cavity are related through the relation

$$Finesse = \frac{FSR}{\Delta\nu} \tag{4}$$

where $\Delta\nu$ is the linewidth of the cavity's resonant condition. Using the estimated finesse and FSR of the OEC, the linewidth of the cavity is approximately 250 Hz. This extremely narrow linewidth necessitates the usage of feedback to keep the laser locked to the cavity, which will be covered in depth in the methods section.

A last key concept relating to the OEC is mode matching. When coupling the input laser beam, which has a Gaussian profile, into the optical cavity, only a certain set of transverse electromagnetic (TEM) modes, are allowed by boundary conditions [4]. To efficiently couple

power into the cavity, we want to match the incoming beam shape to the fundamental $\mathrm{TEM}_{00}$ mode, avoiding excess power into higher order modes (HOMs).

To mode match, the beam's Gaussian shape described by the q-parameter

$$q(z) = z + iz_R, \qquad z_R = \frac{\pi w_0^2}{\lambda}, \tag{5}$$

where $w_0$ is the beam waist, $z$ the distance, $z_R$ the Rayleigh range, and $\lambda$ the wavelength, is shaped utilizing lenses to spatially match the cavity's $\mathrm{TEM}_{0,0}$ eigenmode at the input mirror. To find the shape of the $\mathrm{TEM}_{0,0}$ eigenmode, ABCD matrices are utilized.

Within an optical system, the propagation of a Gaussian beam can be described by ABCD matrices, with optical components such as mirrors, beam splitters, and lenses having unique transfer matrices, covered in Ref. [4].

To find the $\mathrm{TEM}_{0,0}$ eigenmode of the optical cavity, we require that the mode must reproduce itself after each round trip. This gives the condition

$$q_{cav} = q_1 = \frac{Aq_1 + B}{Cq_1 + D}. \tag{6}$$

Which can be rearranged to give the following quadratic equation

$$Cq_{cav}^2 + (D - A)q_{cav} - B = 0 \tag{7}$$

By solving this equation, we can solve for $q_{cav}$, and find the eigenmode's waist size, location, and spot size at the input mirror. Once these parameters are known, a mode matching solution utilizing two to three lenses is found to match the beam's q-parameter to $q_{cav}$ as closely as possible, maximizing the circulating power into the cavity [4].

# 3 Project Objectives

The primary objective of this project is to demonstrate pulse locking of the laser to the OEC. Prior work with the OEC has achieved stable locking to an ultra-high-finesse cavity with the laser operating as a continous wave (CW), however, additional challenges arise when attempting to lock the cavity with a pulsed laser [3]. This is because in order for a coherent build up of optical pulses to occur, the FSR must precisely match the pulse rate of the laser. Additional challenges also arise when attempting to maintain a stable lock to the cavity with a pulsed laser, as you no longer have a continuous signal for the locking loop. Addressing and overcoming these challenges will be an integral part of this project, and the techniques developed and learned will be utilized within BLF's larger 15 m and 150 m cavities. To achieve the larger objective of pulse locking, this project seeks to achieve several smaller goals outlined below:

**Integrate new mirrors and realign cavity**

A new set of 3.4 ppm loss mirrors have been delivered for usage in the OEC. The first objective of this project is to implement these new mirrors, and to realign the cavity with a new mode matching solution implemented.

**Achieve a stable continous wave lock to the OEC**

After the OEC has been realigned, we will reestablish a stable lock to the cavity's $TEM_{0,0}$ mode through a Pound-Drever-Hall (PDH) lock.

**Characterize pulse shape**

Once the cavity has been aligned and locked, we will begin to characterize the pulsed laser. This will include understanding the temporal pulse shape, bandwidth, and electronics involved in generating and observing the pulses.

**Perform pulse locking on OEC**

Once the pulses have been characterized, we will lock the pulsed laser to the OEC by dithering, or slowly varying the laser. If time permits, we will also investigate an improved form of locking through balanced homodyne readout.

**Analyze results and address limitations**

Since the OEC is a demonstration cavity, a key objective is to understand and interpret the procedure, limitations, and effectiveness of pulse locking to the cavity. The techniques we use and develop can then be adapted to the larger BLF cavities in development.

# 4 Methods

An overview of the approach that will be utilized to achieve our objectives for this project is provided below.

**Aligning Cavity**

The first step in this project is to integrate the new 3.4 ppm loss mirrors within the OEC. This will require a new cavity mode matching solution to be computed. After this, the cavity will be realigned with the updated mode matching lens integrated into the current OEC setup described in Fig. 1. This process is covered in more depth in the Progress section.

**Laser Frequency Stabilization Utilizing PDH Locking:**

After implementing the new mirrors and realigning the cavity, we will want to stabilize the laser frequency utilizing the PDH locking technique. This method is covered in depth in Ref. [5], with key details overviewed here.

A first step to performing a PDH lock to the reference cavity will be to use an EOM to generate frequency sidebands of the laser, resulting in a central carrier frequency and a sideband above and below the carrier frequency. This light is then directed into the cavity, with the sidebands reflecting at the input mirror, while the carrier light enters the cavity, acquiring a phase shift before it leaks out. The combination of this leakage light and the reflected light is then directed onto a photodetector which generates a signal that contains information about the carrier frequency difference from resonant frequency of the cavity.

This signal is then passed through a mixer and a low pass filter, extracting a DC error signal. This error signal is antisymmetric about the cavity resonance, and crosses zero at resonance,

making it suitable for feedback. We will utilize a Proportional-Integral-Derivative (PID) loop, to provide feedback on the laser frequency and minimize the error signal over time, locking the laser to the cavity. A generic schematic of the PDH setup is shown below for reference.

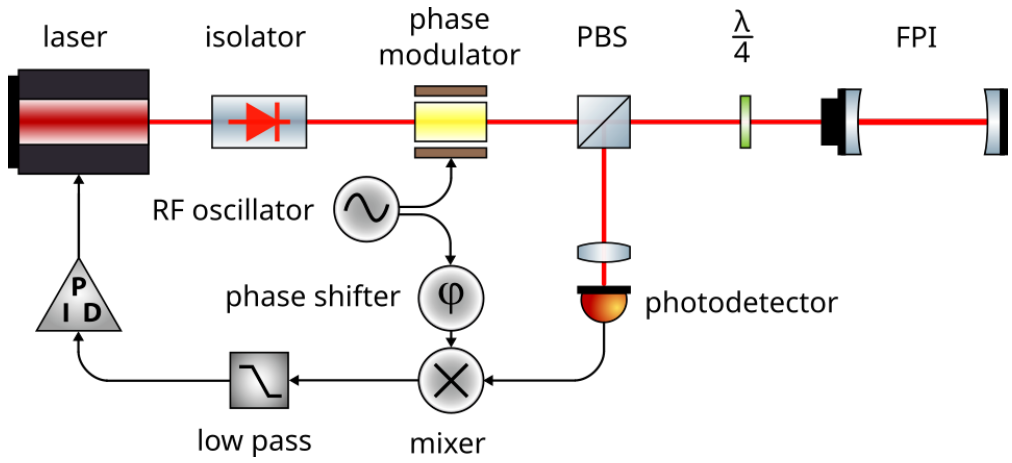



Figure 2: Schematic of a PDH locking setup for stabilizing a laser to an optical cavity. Adapted from Ref. [6].

With the laser stabilized, we will obtain a precise measure of the cavity finesse and FSR.

**Pulsed Laser Operation:**

After we have achieved a stable lock of the laser operating in CW mode to the OEC, we can transition to performing pulse locking. Because we want to coherently stack light, enhancing the circulating optical power within the cavity, the incident laser pulses must precisely match this FSR. In other words, we want $f_{rep} = \Delta\nu_{FSR}$, the repetition frequency of our laser pulse to match the FSR.

Because of this requirement, prior to implementing pulsed operation of the laser we will want to characterize the laser pulses, ensuring the pulse bandwidth and shape are compatible with the OEC. The pulses can be characterized utilizing a fast photodiode (PD) outputting to a high bandwidth oscilloscope, where the pulse shape and repetition frequency can be measured. At this step it will be important to ensure our PDs are sufficiently fast such that they can accurately resolve the sharp edges of the fast pulses.

For this project, the pulse duration we are targeting is 1 nanosecond (ns), with pulses at the FSR rate, roughly once every 10 ns. The laser pulses will be generated by a Mach-Zehnder EOM, allows us to modulate intensity at a high frequency.

After characterizing the laser pulses, we can begin locking the pulsed laser to the cavity. As previously mentioned, matching the repetition frequency to the FSR is a strict requirement to achieve coherent buildup. A method to achieves this is by dithering, or modulating the pulse rate of the laser. As the laser is dithered, a PD can be utilized to measure the transmission of incident light through the cavity, generating an error signal. This error signal can be utilized as feedback to the Mach-Zender EOM to ensure pulses are constructively stacking in the cavity.

**Address Limitations of Pulse Locking Scheme:**

At this stage of the project, we should have achieved a stable laser that can follow changes in the OEC FSR, while also locking the pulse rate to maximize enhancement within the cavity via dithering. However, we must also address limitations within the setup, such as potential instabilities of the PDH lock, PDs that are too slow, and the length we can achieve a pulse lock. We should also consider whether our pulses are well-defined and not distorted to allow for efficient coupling to the OEC. A key final step in the project will be to analyze these potential limitations, and others that may arise, in order to determine potential solutions.

# 5 Progress

During the first week of this project, I gained familiarity with the cavity setup with simulations through the Finesse Python package. In Finesse, I modeled the OEC and the expected error signal derived for the PDH lock, as well as the generation of higher order modes from cavity misalignment. I also read several papers in relation to cavity mode matching and the ABCD matrix formulation for optics.

During the second week the new set of cavity mirrors with 3.4 ppm loss and radius of curvature of 15 m were installed. Because of this new setup, a new alignment for the cavity as well as a new mode matching solution was required. The cavity was aligned by carefully steering the beam with the external mirrors until we visualized a clean $TEM_{00}$ mode on the transmitted and reflected CCD cameras. The aligned beam path was marked with a set of 5 irises for future realignment.

I then profiled the laser beam to obtain the waist location and waist quadrature measurements necessary for obtaining a new mode matching solution for the cavity. To profile the beam, a WinCamD beam profiler was set in the beam path after the Faraday isolator (FI), where z=0 denotes the edge of the FI shown in Fig. 1. DataRay software was utilized to take a set of 5 waist measurements as I moved the profiler 5-10 mm at a time in reference to a ruler. The waist versus distance data was then imported into Python to fit the data to the waist equation given by

$$w(z) = w_0\sqrt{1 + (\frac{z}{z_R})^2} \tag{8}$$

where w(z) is the waist as a function of distance, and $z_R$ is the Rayleigh range. Utilizing Scipy curvefit, the following fit was found from the data:

X(u): $w_0$ = 60.26 +/- 0.21 um, z0 = -45.30 +/- 0.43 mm, $z_R$ = 10.72

Y(v): $w_0$ = 61.07 +/- 0.14 um, z0 = -46.74 +/- 0.30 mm, $z_R$ = 11.01

The fit versus distance along with the residuals is shown below.

After profiling the beam, the waist, waist position (z0), and Rayleigh range were utilized by Peter Carney to compute a new mode matching solution for the cavity following methods discussed in the background section.

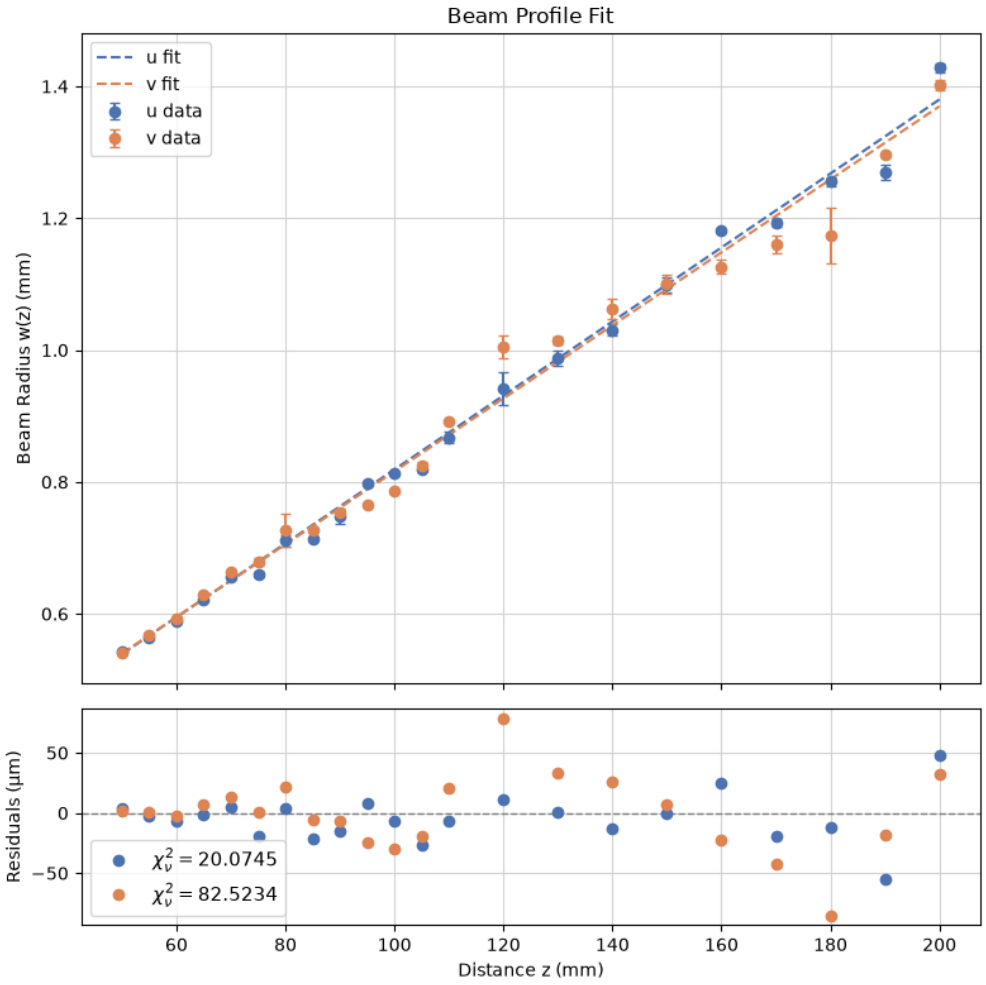



Figure 3: Gaussian beam fit (top) and residuals of fit (bottom).

The solution found consisted of two lens, Lens 1 at z=149.5 mm after the FI with focal length of 0.200 m, and Lens 2 at 399.4 mm after the FI with focal length of 0.750 m. The lens and their locations are showcased in Fig. 1. After implementing the lens, the beam was aligned to the cavity by steering through all 5 irises.

With the beam coarsely aligned through the irises to the cavity, the transmitted CCD camera was used to visualize the cavity's modes. An aligned cavity will showcase a strong $TEM_{00}$ mode, with little to no HOMs present. HOMs were initially present indicating misalignment of the beam. The beam was finely walked and the lenses translated with a linear stage until a strong $TEM_{00}$ peak was observed.

At this stage, we have implemented a new set of highly reflective mirrors, reprofiled the beam, found a corresponding mode matching solution, and realigned the cavity. Our next steps are to lock the cavity to the $TEM_{00}$ mode utilizing the PDH procedure. After this, we can measure the FSR of the cavity, and proceed with pulse locking of the laser.

# 6 Challenges

A key challenge encountered during the first stage of this project is the narrow linewidth of the cavity. Since the linewidth of the OEC is on the order of 250 Hz, extreme precision is required to align to the cavity's $TEM_{0,0}$ mode. This challenge will be present throughout the project, and will require high precision when steering mirrors and lenses. Because the input mirror is enclosed within the UHV chamber, this process is also challenging as we can not adjust the input and output coupling mirrors once under vacuum.

A future anticipated challenge will be performing pulse locking of the cavity. Pulse locking requires precise matching of the laser pulse rate to the FSR of the OEC. To do this, a dither lock will be employed by varying the laser frequency through current control. However, the dither lock itself will be limited by the speed of the electronics present within the feedback loop, including the PD bandwidth utilized to visualize the pulse and the internal clock speed of the moku pro utilized as the signal generator.

Lastly, because of the large enhancement factor of the cavity, extremely high circulating powers of several kilowatts have been achieved through past work on the OEC. This high circulating power can lead to unwanted thermal effects, such as thermal lensing, which further challenge maintaining the cavity lock. If significant thermal effects ocurr, we may need to lower the circulating power.

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The proposal objectives and approach were also developed with help from Dr. Georgia Bolingbroke, Postdoctoral Scholar in Physics at Caltech