Chapter 4

The Thermal Noise Interferometer

4.1 Introduction

The purpose of the Thermal Noise Interferometer (TNI) project is to build a low-noise interferometer capable of determining the fundamental noise sources that would limit LIGO's sensitivity. Using materials and designs from LIGO, the TNI can be used to measure the noise in test mass mirrors, suspension systems, and control electronics. It is one of the more sensitive displacement measuring devices on Earth, with an rms length noise of 5×10^{-18} m/rHz at 1kHz.

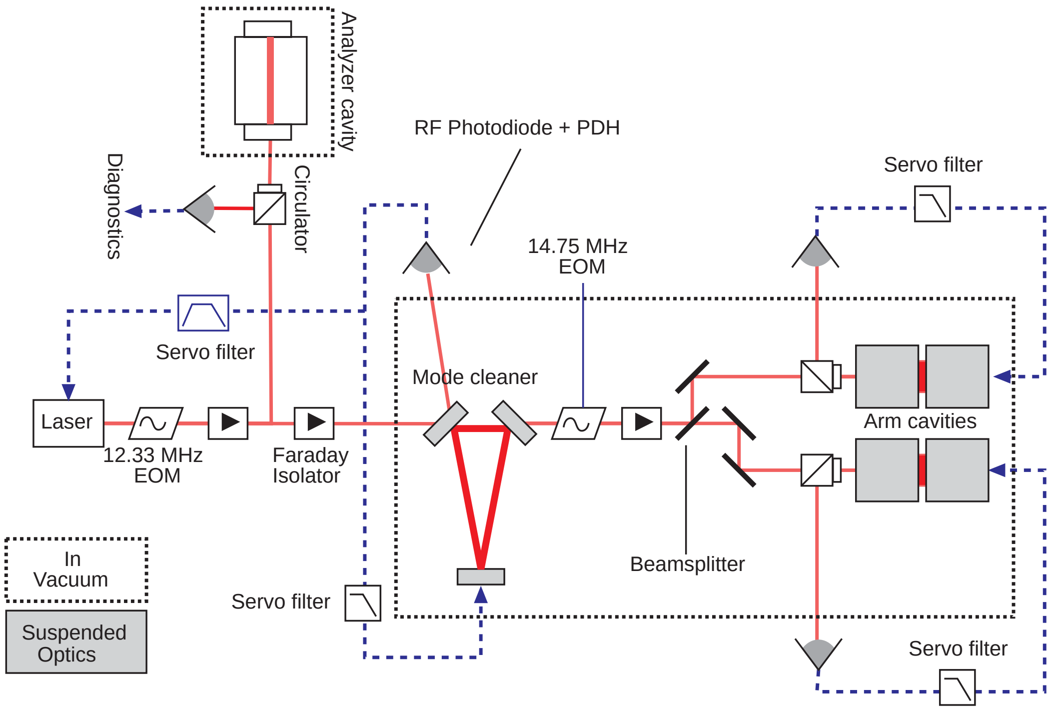
This chapter describes the steps necessary to build and operate an instrument like the TNI.

4.2 Design

The design of the TNI is modelled after that of LIGO. A schematic of the major components is shown in Fig. 4.1. The TNI has two arm cavities made from suspended, high-Q mirrors under vacuum, and data are taken as the difference between the signals from the two arms. To optimize the TNI for detecting thermal noise instead of gravitational waves, its arms are very short (8.5 mm) and the laser spot is very small (.15 mm). The arms are adjacent and parallel, so that seismic vibrations affect them equally. As in LIGO, the mirrors are supported only by a wire sling, so they move with minimal friction. A triangular, suspended cavity in the vacuum chamber provides a frequency reference for the laser and acts as a mode cleaner, without creating any spurious interferometers. Also like in LIGO, the Pound-Drever-Hall (PDH) [43, 41] method is used for sensing cavity length and laser frequency changes.

The in-vacuum optics are all mounted on a seismic isolation stack [52, 50], and the interferometer mirrors are further removed from ground noise by 1-Hz pendulum suspensions. The suspended

Figure 4.1: Conceptual design of the TNI, showing the major optics and servos.



(4.1)

mirrors have local damping servos to reduce the pendulum Q, but the servos roll off strongly above 20 Hz so that the mirrors are essentially free masses above 300 Hz.

Three control servos are needed to keep all the interferometers resonant simultaneously. The mode cleaner is locked to the laser at low frequencies, but the laser is locked to the mode cleaner at high frequencies. The two arm cavities are independently locked so as to not have any common-mode electronic coupling.

4.2.1 Optics

The central component of the TNI (Fig. 4.2) is the laser, a 500 mW, 1064 nm diode-pumped Nd:YAG non-planar ring oscillator (LightWave Electronics Model 126), similar to the one described in the previous chapter. The beam emanating from the laser is only slightly elliptical, so a pre-mode cleaner is not needed as with LIGO.

Immediately after the laser, a tuned electro-optic modulator (EOM) (1) (New Focus #4003) applies 12.33 MHz RF sidebands. The modulation depth is weak ($< 0.1\%$) to minimize the beat with the arm cavity sidebands. The EOM is misaligned to the beam by a few degrees, so that reflected light does not feed back to the laser crystal. A Faraday Isolator (2) and half wave plate (3) follow the EOM to prevent back-reflections from downstream optics. A lens (4) refocuses the beam as it passes through another Faraday Isolator (6). A beamsplitter (5) diverts 10% of the beam power for measuring the laser frequency noise with an independent cavity.

In the main beam, a wave plate (7) sets the beam into vertical polarization (though horizontal may also be used) for the mode cleaner (see §4.2.2), and steering mirrors (8) maneuver the beam into position for the periscope (9). At the top end of the periscope, a mode-matching mirror (10) images the beam waist for the mode cleaner. This mirror is mounted on a steel pedestal which is clamped to the underside of an elevated platform. The steering mirror at the top of the periscope (also clamped to this platform) directs the beam through a window and into the vacuum chamber, where mirrors line it up with a periscope (11). The top mirror of this periscope and another steering mirror (12) align the beam to the mode cleaner, made from three suspended mirrors (13, 14, 15). The rejected beam from the mode cleaner is pointed (16) back through the window and onto the main table, where steering mirrors (17) lead it to the mode cleaner photodiode (18).

The beam transmitted by the mode cleaner wraps around the back of the table, passing through a mode-matching lens (19) which images a waist at the 14.75 MHz EOM (23). A $R \sim 99\%$ steering mirror (20) transmits a fraction of this beam, which is lowered by another periscope (21) and sent through a window to a TV camera (22). The TV camera shows which mode is resonant in the cavity.

After the EOM (23), the beam transmitted by the mode cleaner turns (24) toward the arm cavities and passes through another Faraday Isolator (25). The magnetic field from this isolator affects all the suspended mirrors, so they have to be aligned after the isolator position is fixed. After the isolator, a half wave plate (26) sets the beam in horizontal polarization for the arm cavities. A mode-matching lens (27) images the arm cavity beam waists, and the beam is turned (28) at a point equidistant from both cavities.

A 50% P-polarization beam splitter (29) separates the beam to the North and South arms. The alignment to the North arm (32) is controlled by adjusting the beamsplitter and a steering mirror (30), so it has to be aligned before the South arm. The transmitted beam is lowered (33) and imaged onto a camera (22) on the monitoring table outside the vacuum. Immediately before the cavity, a circulator diverts the reflected beam from the North arm around the table to a periscope (35, 36) and back to the main optics table (37), where a periscope (38) directs the beam to a RF photodiode [86, 112] (40). A large, fast cat's eye lens (39) focuses the beam onto the photodiode so that the detected light power is not affected by beam jitter.

The beam transmitted by the beam splitter (29) is aligned with a pair of steering mirrors (41) to the South arm (42). The transmitted beam is also directed out of the chamber (44, 45) through the side window to a video camera to monitor the cavity mode. The beam reflected from the cavity is diverted by a circulator (43) and steering mirrors (46, 47, 48) to the main optics table. There, as with the other arm, a periscope (49) and cat's eye lens (50) focus the beam onto the RF photodiode (51).

4.2.2 Mode cleaner

The triangular mode cleaner uses 3"Ø $\times$ 1" mirrors in LIGO-like small-optic suspensions. The input and output mirrors (13, 14) are flat, superpolished, with T=300 ppm 45° HR coatings on the front surfaces, and AR coatings on the back surfaces. They have a half-degree wedge, oriented so that the wide edge is up. This arrangement makes the pitch, yaw, and Z modes of the pendulum have resonant frequencies all around 1 Hz. The back mirror is a 3"Ø $\times$ 1" superpolished plano-concave mirror with a 5 m radius of curvature. Its front side has a T=30 ppm normal incidence HR coating, and the back side is AR coated. Polishing and coating were done by Research Electro-Optics (REO) in Boulder, CO.

A local damping system prevents the mode cleaner mirrors from swinging around at low frequencies. Magnets and fins are glued to the back of the mirror (Fig. 4.3), which fit into an Optical Sensor / Magnetic Actuator (OSEM) on the suspension cage (Fig. 4.4).

4.2.3 Arm cavity mirrors

The arm cavity suspension hardware can accommodate any 10 cm high-reflectivity mirror. The mirrors currently in use are fused silica with $T = 300$ ppm HR coatings, polished and coated by REO. The TNI lab has available sets of $T = 300$ ppm sapphire mirrors which can be used in future studies.

As with LIGO mirrors, they have magnets on aluminum dumbbell standoffs [55] attached to their side and back for local damping. To minimize the mirror's magnetic dipole moment, the orientations alternate for the magnets on the back surface [62].

Figure 4.2: Top view of optics layout. The mode cleaner can operate in either horizontal polarization for low finesse or in vertical polarization for high finesse.

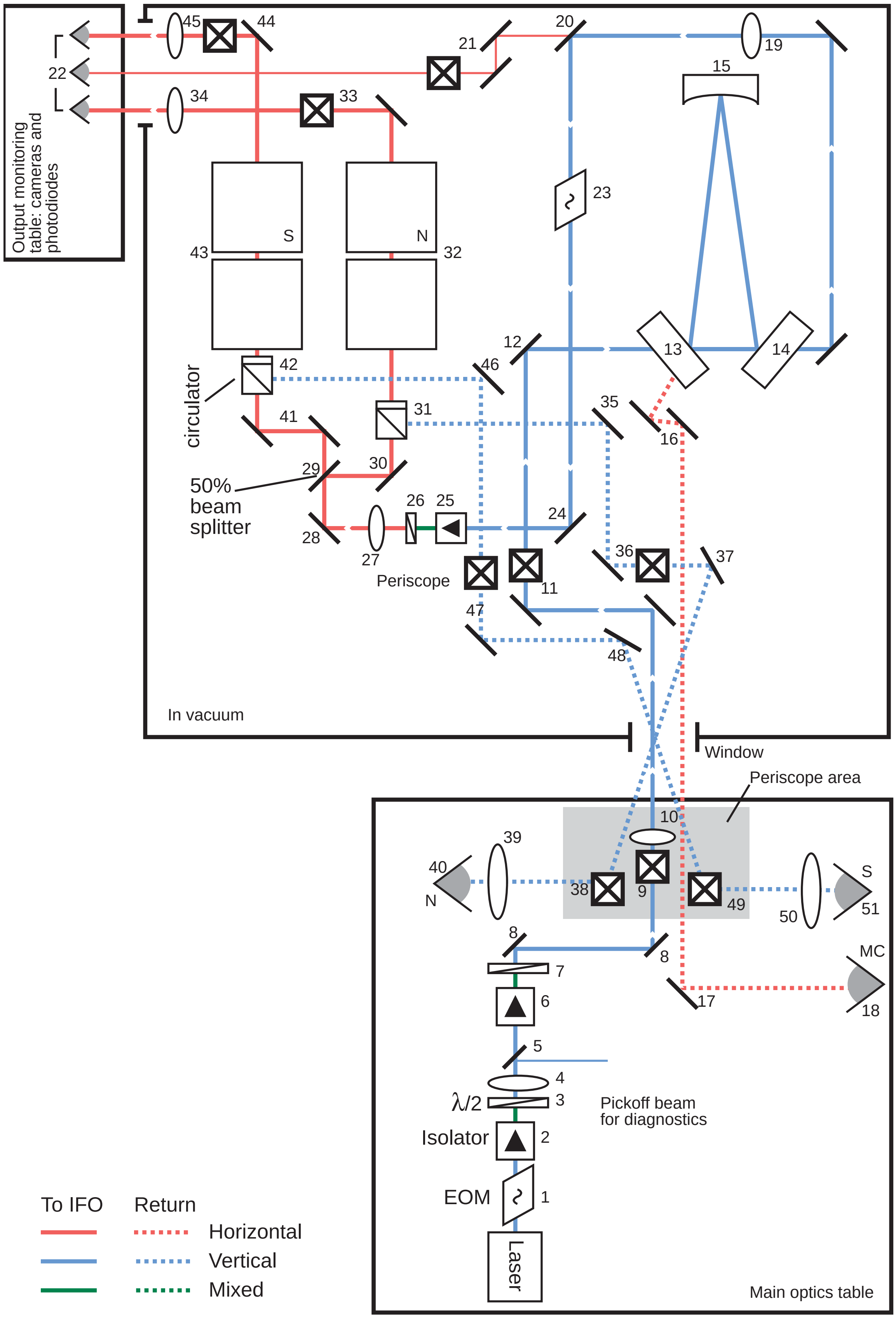


Figure 4.3: Back and side view of a mode cleaner mirror at 50% scale, adapted from [79]. The line above the side fin indicates the position of the wire standoff.

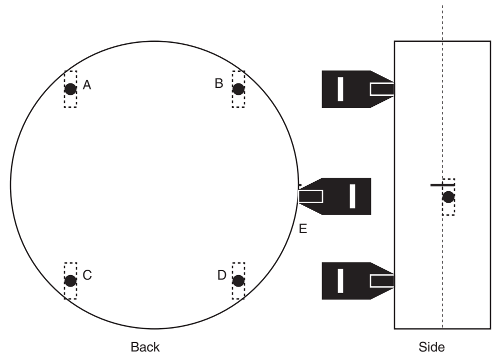
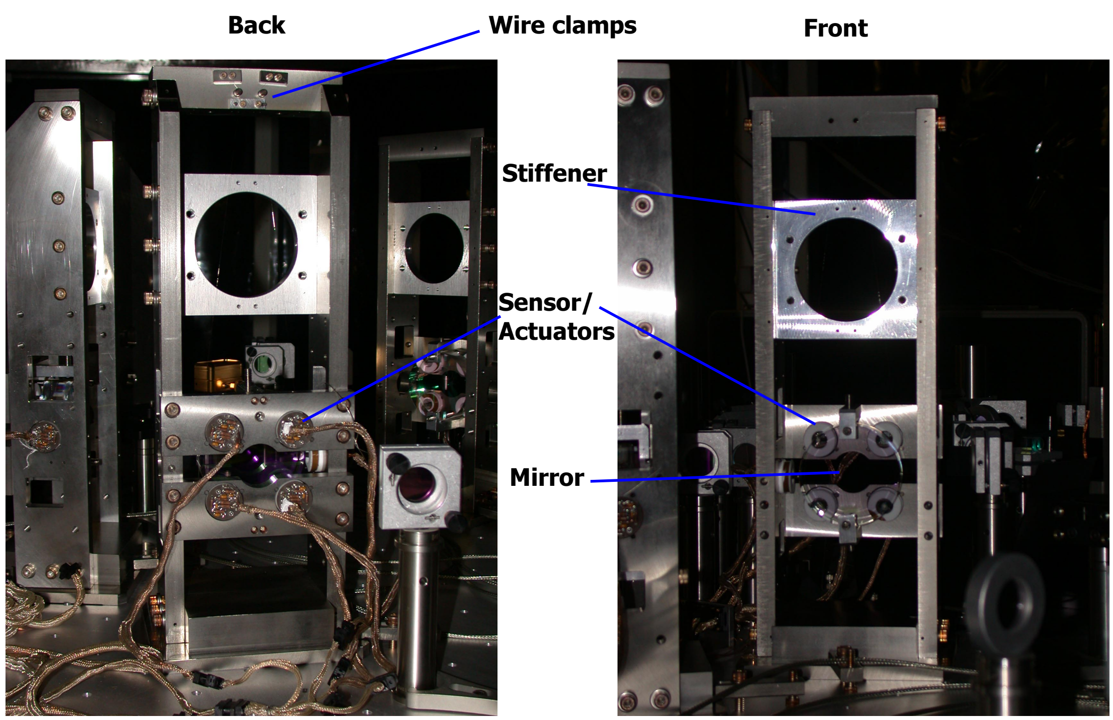


Figure 4.4: Mode cleaner suspension towers.



4.2.4 Mechanics

The mechanical structures of the TNI are designed to reduce seismic noise. A vibration isolation stack [52, 50] supports the optics table for the mode cleaner and arm cavities. On top of isolation stack, the suspended interferometers themselves are in pendulum suspensions [61]. The main optics table holding the laser simply rests on the ground.

4.2.4.1 Seismic isolation

The vibration isolation system (Fig. 4.5) is a 4-layer stack of steel and elastomer.[1]

Wires are anchored to the support blocks to minimize vibration transmission. Electrical feed-throughs are on the bottom part of the chamber, while windows are on the top part. The vacuum chamber is supported by one set of legs (see Fig. 4.5), while the instrument table rests on a separate set of legs.

4.2.4.2 Suspensions

The mode cleaner mirror suspensions (Fig. 4.4) are modified LIGO Small Optic Suspensions (SOS) [61]. These consist of an arch of stainless steel[1] with two crossbeams to hold the OSEMs. The main difference between these and LIGO SOSs is that these use C-clamps with set screws for earthquake stops to lower their cost. The mirrors are supported by a loop of steel music wire clamped at the top. The SOSs are designed to have resonant frequencies outside the bandwidth of the local damping servo: for a LIGO SOS tower, the vertical resonance frequency is 16 kHz and the lowest measured internal mode is at 156 Hz [70].

The arm cavity mirror suspensions are scaled up versions of the SOS (Fig. 4.6). Each suspension cage holds two mirrors, with the suspension wires clamped to the same piece of metal.

4.3 Mode cleaner and laser servo

A feedback servo system locks the mode cleaner and laser to one another (Fig. 4.7). At low frequencies, the laser is a stable reference for the suspended mirrors of the mode cleaner. At high frequencies, the cavity has much better frequency stability than the laser.

[1]This is the same stack used at the LIGO Phase Noise Interferometer [50].

[1]Type 304, non-magnetic, free-machining stainless steel, with an aluminum stiffening plate. Type 303 stainless is not suitable for precision machining of large parts since magnetic steels will attract the mirror magnets, and mounting the OSEMs in a high-conductivity metal like aluminum can lead to greater eddy-current damping.

Figure 4.5: Side view of the opened vacuum chamber. The two arm cavities are on the left, and the mode cleaner is on the right. Counterweights by the mode cleaner balance the weight of the arm cavity suspensions.

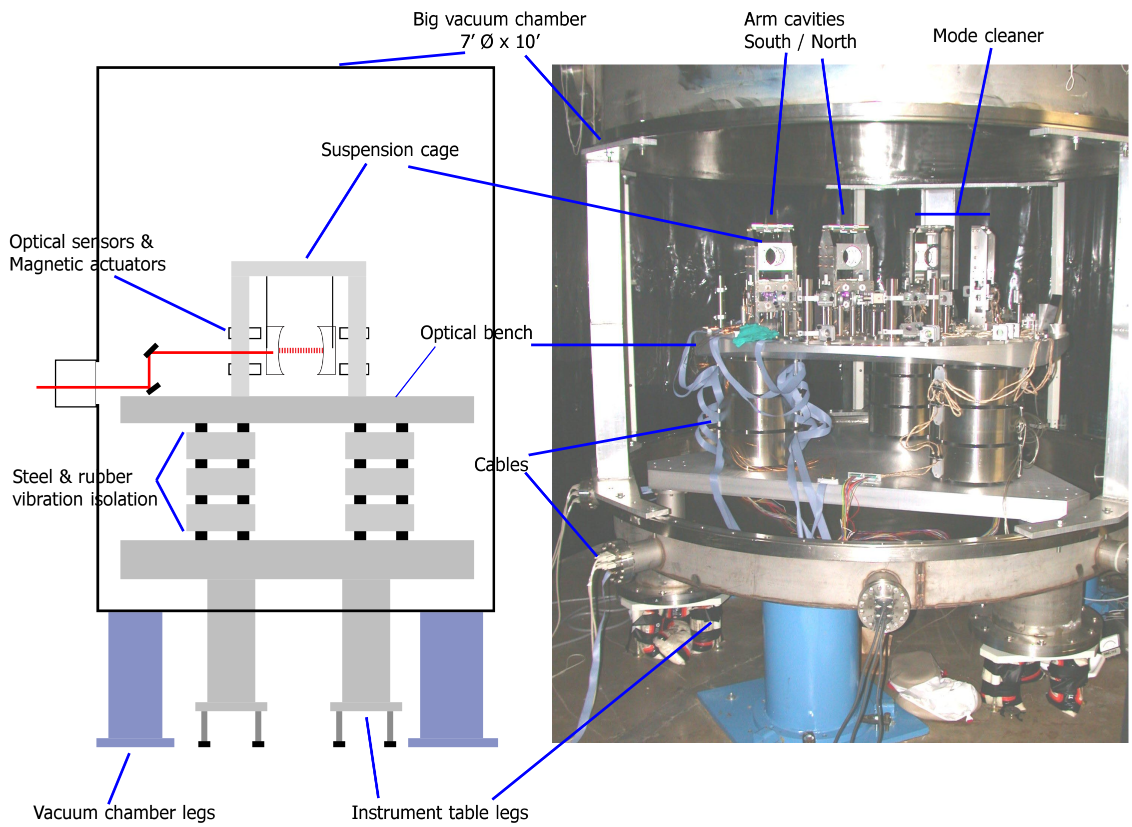


Figure 4.6: A 10 cm arm cavity output mirror. The OSEMs are visible as white rings with red bands behind and to the left of the mirror. The white bars in front of the mirror are Teflon earthquake stops.

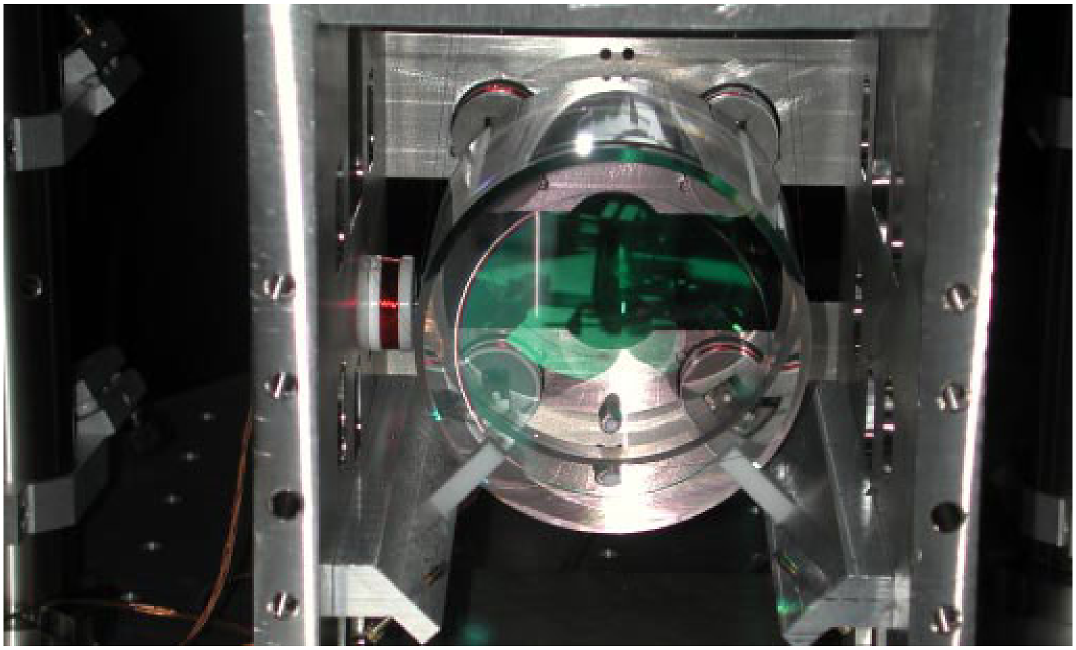
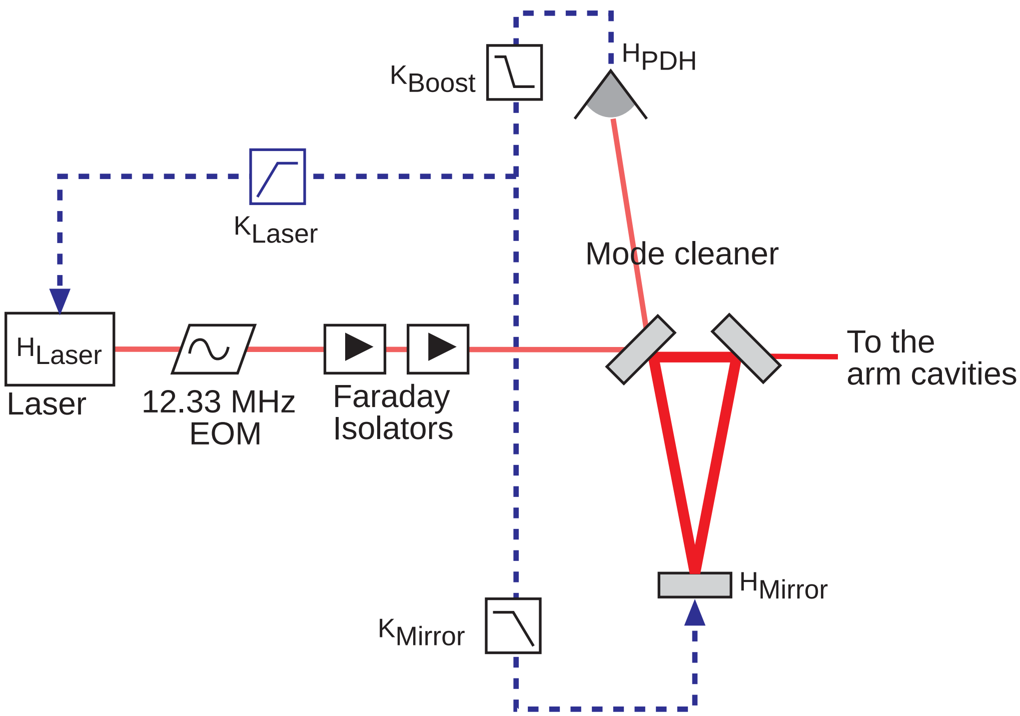


Figure 4.7: Mode cleaner servo



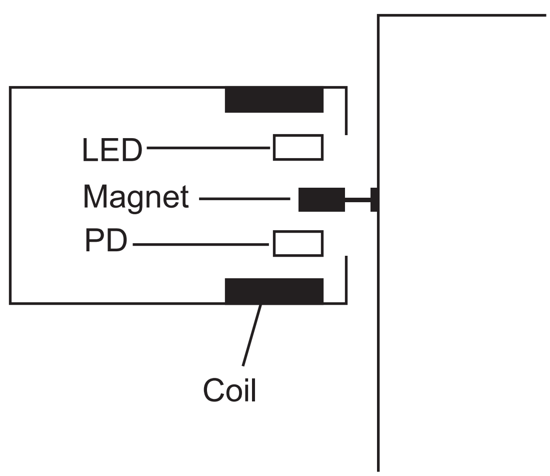
The laser PZT bandwidth is 120 kHz [75], which allows frequency noise suppression up to 90 kHz (see §4.3). If the servo gain is raised so that the unity gain frequency is higher than 90 kHz, servo oscillaions occur. Schematics of the servo electronics are documented in LIGO technical notes T000077 and T010023 [18, 17].

4.4 Local damping

Each mirror's OSEMs (from the LIGO 12 m mode cleaner prototype [2]) are powered by a single OSEM controller [33] which acts by velocity damping. From the 4 sensors on the back of the mirror, the controller computes the mirror's displacement in the yaw, pitch, and Z degrees of freedom. These are differentiated to get the velocity, and a voltage proportional to the velocity is applied to the OSEM magnet coils. A 6-pole Butterworth filter at 22 Hz suppresses feedback at high frequencies. The local damping unity gain frequency can be set by adjusting the electronic gain in the OSEM controller.

The mode cleaner OSEMs have a split photodiode and an infrared LED on opposite sides of the fin. When the slit moves about the center of the photodiode, the OSEM produces a voltage proportional to the displacement (see §4.4). The OSEM controller then drives current through a coil in the OSEM, which suppresses motion relative to the suspension tower.

Figure 4.8: Optical Sensor Electro-Mechanical actuator (OSEM)



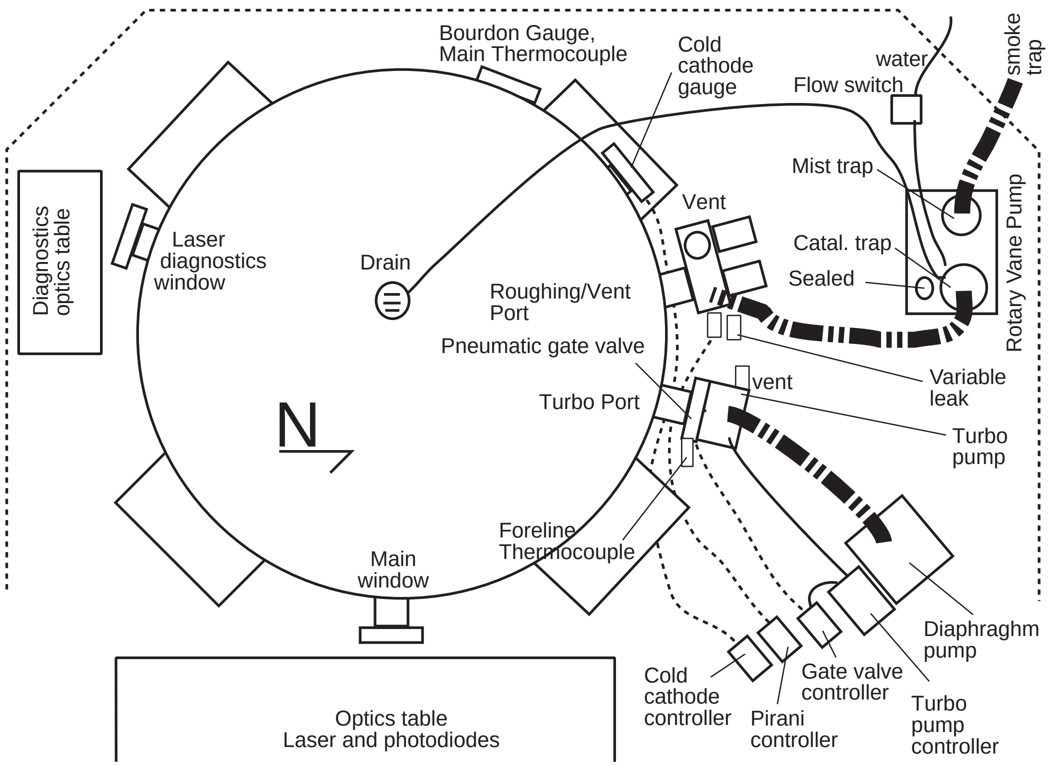
The arm cavity OSEMs (Fig. 4.8) are similar, only they have a single photodiode instead of a split photodiode. For both types, the effect of the local damping system is to reduce the pendulum

Q while preserving its high-frequency noise suppression.

4.5 Vacuum equipment

Since the interferometers are not very long in the TNI, the vacuum requirements are less stringent than for LIGO. For the TNI's 1.5 kg, 10 cm fused silica masses, gas damping in a vacuum of 10^{-6} Torr limits the Q to 10^{7} (Eq. **??**).

Figure 4.9: TNI vacuum equipment



The primary pump is a rotary vane roughing pump[2] (Fig. 4.9). The pump's exhaust valve has a two-stage filter: a commercial mist trap, and a bucket of kitty litter. The input valve has a catalytic oil trap on the foreline to break down oil migrating back into the chamber. The oil trap operates at 250° C, and uses water cooling to keep the case from becoming a safety hazard. To further prevent oil contamination, a pinhole leak at the beginning of the foreline limits the pressure the roughing pump can reach to about 150 mTorr [121].

After the roughing pump has finished its job, the foreline valve is closed and the turbo pump

[2] Alcatel model 2063CP

takes over. The turbo pump[3] is attached to the chamber at a separate port via a pneumatic gate valve. The gate valve is interlocked to the turbo pump, and closes if the power fails or if the pump speed falls below 42krpm, which can happen if the gate valve when the pressure inside the vacuum chamber is too high. The turbo pump is backed by an oil-free diaphragm pump[4].

The vacuum pressure can be observed by a Bourdon (bellows) gauge from atmosphere to 25 Torr, a Pirani gauge[5] from 20 torr to 10 mTorr, and a cold-cathode gauge[6] below that. It takes about 4 hours to pump down from atmosphere to 150 mTorr, and a day to pump down from there to 10^{-4} Torr. It takes several days after that to reach the lower limit of about 10^{-7} Torr. Fortunately, the instrument locks in air so long as the chamber is closed.

4.6 Results and summary

At the end of 2001, with only one arm cavity running, the TNI reached the 10^{-18} m/rHz noise level. After a year of upgrades and improvements, both arms run reliably and robustly, with matched sensitivities of $\sim 5 \times 10^{-18}$ m/rHz at 1 kHz. At this level, the noise is dominated by seismic noise at low frequencies and laser frequency noise at high frequency.

Estimates of the detector sensitivity are plotted in Fig. 4.10 and 4.11 [16], along with plausible levels of thermal noise. These data are taken with a Stanford Research 780 network analyzer measuring the power spectrum of the arm cavities' PDH signals. The raw data are then scaled by the inverse of the open-loop transfer function by the method described in the previous chapter.

Pendulum thermal noise is estimated from the wire loss angle 3×10^{-4} [53] and the pendulum dilution factor 1×10^{-2} [111]. The coating structural damping noise estimate is based on the mirror loss angle $\phi_\perp = 10^4$ measured by Harry *et al.* on similar coatings [60]. The substrate structural damping noise estimate is based on the highest bulk Q measured *in situ*, 3×10^6.

[3]Varian model V300 HT
[4]Gremenberger Antriebstechnik Gmbh, model VDEO530
[5]Kurt J Lesker Co, model 902016
[6]MKS Instruments, Coulder CO, model 421

Figure 4.10: North arm cavity sensitivity. [16]

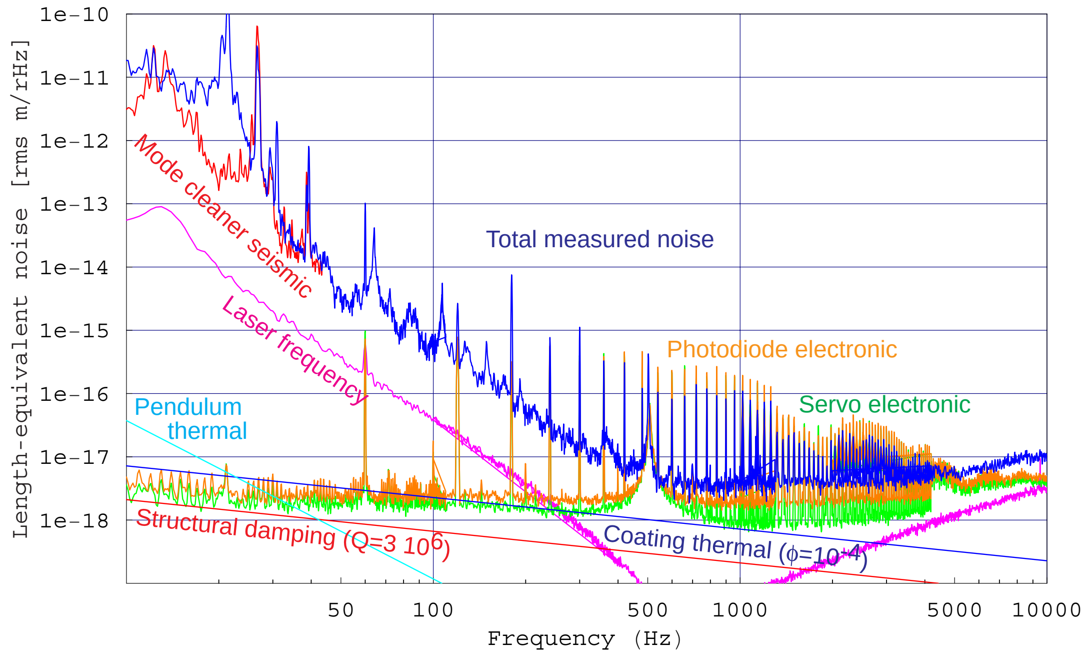


Figure 4.11: South arm cavity sensitivity. [16]