LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Reference Design Document for the Advanced LIGO Input Optics

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1 INTRODUCTION

1.1. PurposeAdvnaced LIGOAdvanced LIGO

The purpose of this document is to define the scope and functionality of the Advanced LIGO Input Optics (IO), to present a baseline design for the IO subsystem based on current Advanced LIGO performance goals, and to examine IO performance limits based on this design. At this stage, detailed system level requirements (SYS) for the Advanced LIGO interferometers have not yet been fully developed. Thus, it is our goal to specify an IO design with sufficient detail to provide a basis for cost estimation and with sufficient flexibility to be able to accommodate SYS level requirements as they become available. Requirements which can be easily inferred from the Advanced LIGO sensitivity goals will be developed.

1.1.1. Top Level Recommendations and Preliminary Conclusions

Based on current knowledge of the Advanced LIGO sensitivity and lockiung scheme, we make the following general recommendations for the Advanced LIGO Input Optics:

- Relaxed frequency noise requirements for the MC indicate that a short MC (16.6 m) should suffice for Advanced LIGO.
- Radiation pressure from the intensity fluctuations[1] in the PSL and OSEM sensor noise are the dominant noise sources at low frequencies (< 50 Hz); a double pendulum may suffice, although a triple pendulum could be used.
- To bring the PSL-induced radiation pressure noise below the required frequency noise, the MC will use large mirrors (20 cm diameter x 10 cm thick). Suspension footprints require that the current beam tube connecting HAM1,2 and HAM 7,8 be replaced with a full LIGO beam-tube (1.25 m diameter tube).
- To meet input jitter requirements, active stabilization of the PSL beam for jitter suppression below the $4 \times 10^{-6} / Hz^{1/2}$ level should be included in the PSL or IO design.
- Preliminary measurements on isolation and thermal lensing in Faraday isolator material provide some comfort that we can handle 150 W powers.
- While serial RF modulation at 150 W may work, alternative modulator architectures should be investigated.
- The mode matching telescope presents little challenge or technical risk in Advanced LIGO, although an analysis of the angular fluctuations of the telescope is required.

1.2. Scope

The IO subsystem scope provides for all aspects of conditioning of the laser light after the PSL and before the IFO input, and direction of the IFO reflected light to ISC. It includes any RF phase modulation of the laser, acquisition and operation of the mode cleaner, mode matching of the light to the IFO, beam steering into the IFO, and the provision of diagnostic signals for ISC.

1. This is not the radiation pressure that comes into the standard quantum limit. Rather, it is a dynamic force term driven by input fluctuations on the PSL beam building up in the mode cleaner cavity.

1.2.1. Hardware

The scope of the IO includes the following hardware:

- electro-optic phase modulators
- Faraday isolators
- variable attenuators
- mode cleaner optics
- mode cleaner length and alignment control electronics
- photodiodes and related electro-optic shutters
- ancillary beam steering optics and opto-mechanical mounts and positioners
- mode matching telescopes for the mode cleaner and the IFO
- mirror suspensions (fabrication only)

The IO specifically does not include the RF oscillator, suspension designs, baffling of scattered light in the HAMs, or RF photodiodes for PSL and ISC diagnostic signals.

1.3. Definitions and Acronyms

- PSL - Prestabilized laser
- ISC - Interferometer Sensing and Control
- COC - Core Optics Components
- SUS - Suspension Control
- SEI - Seismic Isolation
- CDS - Control and Data Systems
- SYS - Detector Systems Engineering
- IFO - LIGO interferometer
- SRD - LIGO Science Requirements Document
- MC - Mode Cleaner
- RF - Radio Frequency
- RFAM - Radio Frequency Amplitude Modulation
- GW - Gravitational Wave
- DRD - Design Requirements Document
- SRS - Software Requirement Specification
- IO - Input optics
- HAM - Horizontal Access Module
- TBD - To Be Determined
- TBR - To Be Revised

1.4. Applicable Documents

1.4.1. LIGO Documents

1.4.1.1 LIGO II Conceptual Project Book, M990288-A

1.4.1.2 Input Optics Final Design Document, T980009-01

1.4.1.3 Mode Cleaner Noise Sources, T960165-00

1.4.1.4 Do wiggle effects depend on mode cleaner length, A. Abramovici et al, LIGO Technical Note #20

1.4.1.5 Beam Jitter Coupling in LIGO II, G. Mueller, T2000xxx

1.4.2. Non LIGO Documents

1.4.2.1 Thermodynamic Fluctuations and Photo-thermal Shot Noise in Gravitational Wave Antennae, V. Braginksy, et al., Phys. Lett. A264, 1 (1999).

1.4.2.2 Suppression of Self-Induced Depolarization of High-Power Laser Radiation in Glass-Based Faraday Isolators, E. Khazanov, et al., J. Opt. Soc. Am B. 17, 99-102 (2000).

1.4.2.3 Heating by optical absorption and the performance of interferometric gravitational wave detectors W. Winkler, et al., Phys. Rev. A44, 7022-7036 (1991).

1.4.2.4 Optical mode cleaner with suspended mirrors, A. Araya et al., Appl. Opt. 39, 1446 (1977).

2 GENERAL DESCRIPTION

2.1. Product Perspective

The primary function of the Input Optics is to provide a temporal and spatial filter of the PSL light so that it is of sufficient stability to be used as a measure of the Advanced LIGO arm cavity lengths. The IO also is responsible for delivering the light with the proper gaussian shape parameters to resonate in the IFO, and to direct the IFO reflected light to the ISC subsystems. Finally, it imposes and monitors any modulation sidebands used for locking alignment sensing and control subsystems.

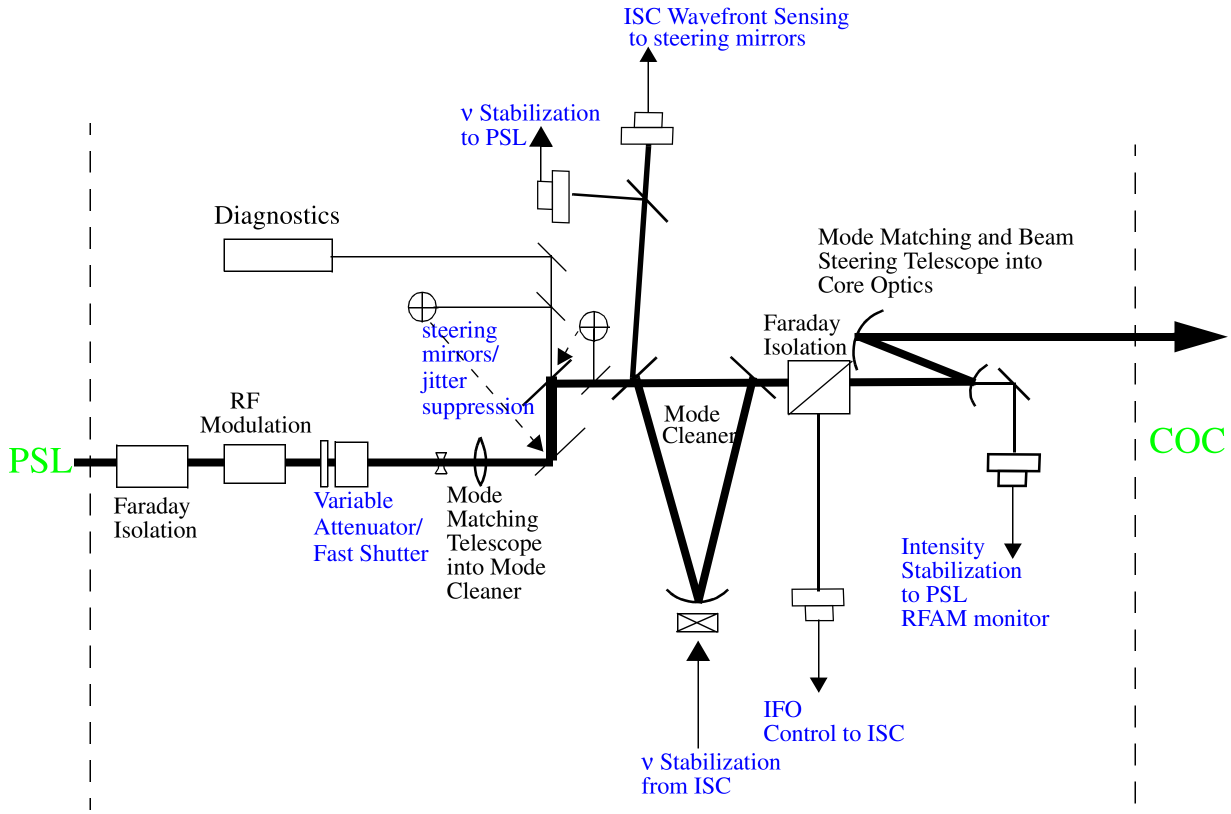

Figure 1: Conceptual layout of IO optical components

2.2. Product Function

The IO conditions the laser light so that its properties are compatible with the primary scientific requirements for the LIGO. This function separates into the following six categories.

2.2.1. RF modulation

The ISC subsystem requires frequency components of the laser light (sidebands) used for length and alignment controls of IFO cavities. The IO must provide for the production and monitoring of these sidebands using RF signals from the ISC.

2.2.2. Mode Cleaner

The laser light must be frequency and spatially stabilized before it can be used to provide length and alignment sensing for the IFO. The mode cleaner provides active frequency suppression through feedback to the PSL, passive frequency and intensity noise suppression above its cavity pole frequency, and passive spatial stabilization at all frequencies.

2.2.3. Mode Matching

The light must be delivered to the IFO with a proper gaussian mode so that it will resonate in the IFO and not be rejected. Thus the IO provides for the mode matching of the light between the mode cleaner and the core optics components of the interferometer. The mode matching telescope must be adjustable to accommodate small deviations from design specification in the core optics. The IO also provides mode matching between the PSL and mode cleaner.

2.2.4. Optical Isolation

Back-reflected light returning to the PSL from optical components in the IFO and IO can couple into the PSL and introduce excess phase noise. Thus the IO must provide optical isolation between the COC and the PSL.

2.2.5. Control beams

The IO provides to ISC two optical beams used for IFO control. The first is from a pickoff after the mode cleaner and gives a signal for intensity stabilization of the PSL. The second (from the Faraday isolator) is the light reflected from the recycling mirror, which gives information on core optics length and alignment.

2.2.6. Diagnostics

The IO must provide diagnostic capabilities for its own functions and for that of other subsystems. Thus includes variable attenuation for laser power control, fast shutters, optical spectrum analyzers, RFAM monitors, and mode cleaner length/alignment sensing and control.

2.3. Constraints, Assumptions and Dependencies

The following factors have been assumed in this document, and are consistent with the requirements spelled out in the Advanced LIGO Conceptual Project Book (See 1.4.1.1).

2.3.1. Advanced LIGO Scientific Requirements

- Displacement Sensitivity (see fig. 4)
  - x (10 Hz) = 3 x 10^{-19} m / $Hz^{1/2}$
  - x (100 Hz) = 9 x10^{-21} m / $Hz^{1/2}$
  - x (1 kHz) = 4 x 10^{-20} m / $Hz^{1/2}$

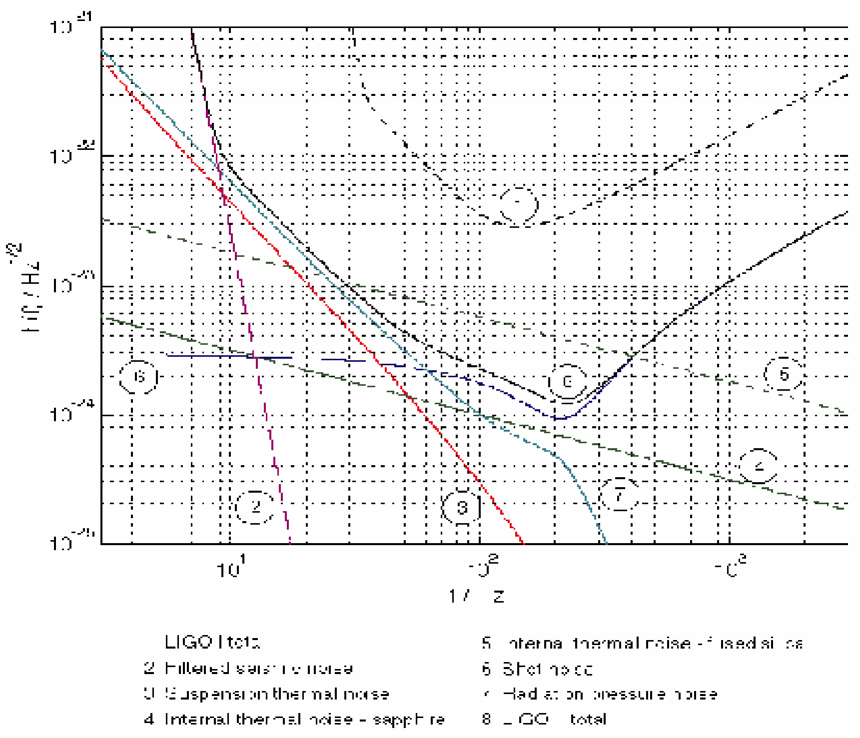

Figure 2: Advanced LIGO Strain Sensitivity

- Gravitational Wave Signal band - 10 Hz to 3 kHz
- Shot noise limited performance
  - h_0 = 1.1 x 10^{-24} / $Hz^{1/2}$ at 200 Hz
- Operational availability - 90%
- Input power (TEM_{00} mode) into the interferometer: 125 W

2.3.2. PSL parameters

- Output power in TEM_{00} mode (at handoff to IOO): 150 W
- Output Power in higher order modes: < 5 W

- Frequency noise: $\delta\nu(f) < 10^{-2}$ Hz/Hz$^{1/2}$, 10 Hz < f < 10 kHz
- Beam jitter: $\varepsilon_1(f)$ ~ 4 x 10^{-6} / Hz$^{1/2}$ f = 100 Hz
- Intensity noise: $\delta I(f)$ / I < 3 x 10^{-9} / Hz$^{1/2}$, 10 Hz < f < 10 kHz

2.3.3. Seismic isolation of suspended optics

- Stack design TBD

2.3.4. Suspensions

- Suspension design supplied by SUS
- COC - Quadruple stage pendulum design TBD
- IO - Single stage pendulum design TBR
  - Large (20 cm diameter) and small (7.5 cm diameter) optics will be used in the IO.

2.3.5. IFO Configuration

- Dual Recycled Michelson interferometer with Fabry Perot cavities in the arms.
- Power recycling cavity length 7.4 to 9.3 m (as LIGO I)
- Schnupp asymmetry less than 40 cm.

2.3.6. IFO Sensing

- DC offset locking/readout of the GW signal
  - First Resonant Sideband: 9.0 MHz
  - Second Resonant Sideband: 180 MHz
- Detailed control topology TBD

2.3.7. Core Optics

- Test Mass Material - Sapphire (TBR)
- COC parameters TBD

3 REQUIREMENTS

3.1. Introduction

The IO subsystem will derive its requirements from the top-level Advanced LIGO requirements for sensitivity and availability. Below, we list the requirements as we currently see them and assign values for those that are known at the present time.

3.2. Performance Characteristics

3.2.1. Overall IO requirements

3.2.1.1 Optical efficiency of Input Optics

The net efficiency of IO TEM_{00} optical power transmission from PSL output to COC input is determined by the requirement that at least 125 W of TEM_{00} light be coupled into the COC. The output power is the sum for the carrier used for GW detection and any sidebands on that carrier. The power at the handoff from PSL to IO is 150 W

Requirement:[1] IO overall transmission > 0.833.

3.2.1.2 Output Beam In-band Amplitude Stability (Jitter)

Alignment fluctuations at the input of the COC couple to angular motion of the test masses to give in-band displacement signals. The (in-band) alignment stability of the entire IO subsystem should not compromise that achieved directly after the mode cleaner, including the mode-matching telescope.[2]

Requirement: The MC must suppress the jitter to a level $\varepsilon_1 < 1.8 \times 10^{-9}$ / $Hz^{1/2}$

3.2.1.3 Parasitic interferometers

Light which reflects or scatters into the Rayleigh angle of the beam contributes to the in-band signal directly (through phase modulation at GW frequencies) and indirectly (through frequency shifting of scattered and reflected light into GW band due to mirror motions).

Requirement: TBD pending data from LIGO I

3.2.1.4 Optical Isolation

Optical isolation is required to separate the PSL from IFO and IO back reflected light.

Requirement: TBD pending data from LIGO I (at least as good as LIGO I; probably better)

1. LIGO II Conceptual Project Book, M990288-A
2. Beam Jitter Coupling in LIGO 2, T000XXX

3.2.2. RF Modulation

The IO provides the optical modulation for the RF sidebands used in the length and alignment sensing. The requirements include modulation frequencies, modulation depths, and relative stability of the mode cleaner resonance and modulation frequency.

3.2.2.1 Modulation frequencies

Modulation frequencies will be determined by LSC. All frequencies (chosen by LSC) must be passed by the mode cleaner and therefore be integral multiples of the mode cleaner free spectral range.

3.2.2.2 Modulation depths

Modulation depths will be determined by LSC. IO must provide for a range of modulation depths for all sidebands consistent with LSC diagnostic requirements.

3.2.2.3 Mode Cleaner free spectral range stability

Detuning of the modulation frequency from the mode cleaner FSR couples with oscillator phase noise to produce amplitude modulation of the transmitted sidebands.

Requirement: TBD pending analysis of effects of RFAM on DC offset locking

3.2.3. Mode Cleaner

The mode cleaner provides frequency and spatial stabilization of the laser light. Requirements are derived from SYS allocations of PSL noise and LSC and ISC light stability demands.

3.2.3.1 Mode Cleaner Frequency Stabilization

The Advanced LIGO frequency noise requirement of 1.0 x 10^{-7} Hz / $Hz^{1/2}$ on the light at the IFO input requires a mode cleaner frequency stability consistent with LSC L_+ loop gains and expected PSL frequency noise.

Requirements:

- Mode Cleaner frequency noise: $\delta\nu(f) < 10^{-5}$ Hz / $Hz^{1/2}$ at f = 100 Hz; 1 x 10^{-6} Hz / $Hz^{1/2}$ at f = 10 kHz[1]
- Shot noise of frequency sensing below frequency noise at all in-band frequencies

3.2.3.2 Mode Cleaner Length Control System Noise

Excess noise in the servo electronics can limit the MC mirror displacement sensing and control.

Requirement:

The length control system will contribute no more than 10% of the limiting displacement noise.

1. LIGO II Conceptual Project Book, M990288-A

3.2.3.3 Mode Cleaner Intensity Stabilization

The light intensity fluctuations at the IFO input consistent with Advanced LIGO specifications assumes intensity stabilization feedback to the PSL from the IO. This stabilization is done after the mode cleaner to suppress beam jitter-induced intensity noise.

Requirement: Intensity noise after mode cleaner - $\delta I(f) / I \sim 3 \times 10^{-9} / Hz^{1/2}$, $40 \text{ Hz} < f < 10 \text{ kHz}$ for both carrier and sideband.[1] (TBR)

3.2.3.4 Mode Cleaner Spatial Stabilization

- Attenuation of TEM_{01} and TEM_{10} modes to a level consistent with ISC beam jitter requirements:[1] $\varepsilon_1 < 1.8 \times 10^{-9} / Hz^{1/2}$
- Attenuation of all other modes by a similar factor (TBD)
- No frequency degeneracy of higher-order spatial modes with the fundamental up to mode 30.

3.2.3.5 Mode Cleaner Alignment

- Low frequency: beam jitter to frequency noise coupling must be kept below the dominant mode cleaner noise source in the 40 - 1000 Hz band,[1]

Requirement:

- $\theta_{rms} < 1.3 \times 10^{-7}$ rad

- In - band: the MC jitter rejection must not be compromised by MC mirror angular noise,

Requirement: $\theta < 10^{-12}$ rad / $Hz^{1/2}$ at 100 Hz

3.2.3.6 Mode Cleaner Beam Centering

The beam spot must be centered in the mode cleaner mirrors to avoid length-misalignment couplings.

Requirement: TBD pending analysis of length-alignment coupling for the MC.

3.2.4. Availability

The IO availability will be limited by the lock acquisition time of the mode cleaner, and any degradation in performance due to thermal stress or optical contamination.

Requirements:

- Lock acquisition time to fully operational state < 20 sec
- Stored light intensity of < 1 MW / cm^2 (TBR)

3.2.5. Mode Matching

The IO mode matching requirements are derived from the system demands of IFO stored power, shot noise on the LSC reflected light signals, and ISC recycling cavity alignment signals.

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1. Beam Jitter Coupling in LIGO 2, T000XXX

3.2.5.1 Coupling efficiency from IO to COC

The coupling efficiency from the Input Optics to the Main Interferometer of the carrier to the COC TEM_{00} mode should be 0.95 or higher. The telescope will provide this level of coupling with adjustability to accommodate deviations in COC specifications. This is for the optimal alignment, and includes both low-order mismatching and more general high-order distortions.

Requirements:

- $\sim 10^{-3}$ $TEM_{01,\,10}$ (TBR)
- $\sim 10^{-3}$ all higher order modes (TBR)

3.2.5.2 Mode matching telescope alignment stability

Perturbations of the mode matching telescope may enhance the coupling of noise sources to gravitational wave noise (in band) and reduce coupling efficiency into COC (low frequency). We require that any telescopic magnification of pointing drift or jitter does not compromise the alignment stability of the IO output beam into the COC:

- Low frequency drift: telescope pointing must be consistent with COC coupling efficiency requirements
- In-band noise: telescope angular and displacement fluctuations must be consistent with ISC requirements for beam jitter at the input of the COC

3.2.6. Diagnostics

The diagnostic mode will provide the means to determine the proper functioning of the IO, and provide measurement of the performance of other subsystems. The following diagnostic capabilities are required of the IO:

- IO Diagnostics
    - complete servo loop transfer function measurements
    - servo electronic noise and null offsets
    - photodiode sensitivity and noise for all IO sensors
    - mode cleaner storage time
    - IO response to laser light pointing, frequency and intensity modulation
    - RFAM on signal after EOMs.
    - Spectral analysis after EOMs
- Diagnostic Services
    - open loop mode cleaner mirror seismic excitation
    - variation in RF sideband modulation depth
    - variation in IFO mode matching efficiency
    - sideband detuning from mode cleaner resonance

4 BASELINE REFERENCE DESIGN

Guided by IO functional requirements and design simplicity, we envision the Advanced LIGO IO to be conceptually quite similar to the LIGO I IO. The schematic layout of the IO displayed in Figure 1 shows the major functional components.

4.1. RF Modulation

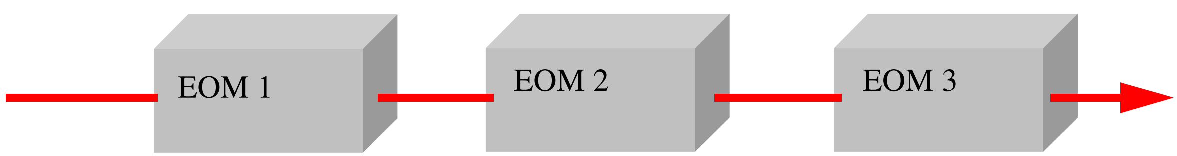
A detailed design of the RF modulation scheme is pending the results of high power testing taking place at UF. The current baseline design is serial modulation of the 150 W laser power using commercial large aperture modulators.

- Modulators: undoped $LiNbO_3$ or KTP
  - resonant, transverse modulation
  - 10 mm x 10 mm clear aperture

High-power testing performed for LIGO I Input Optics indicates that for large aperture crystals, power densities can be kept well below damage thresholds (> 20 KW/cm^2). However, recent conversations with Hagop Injeyan at TRW have indicated that $LiNbO_3$ experiences a substantial photorefractive at 100 W power levels. KTP has been found to be suitable up to 300 W with spot sizes of 2-3 mm. Issues remaining to be investigated include:

- RFAM (both static variations caused by temperature variations coupling to polarization/optical axis misalignment and dynamic variations at the demodulated RF frequency)
- amplitude fluctuations from nonlinear processes (SHG)
- thermal lensing

Contingency modulations schemes (Mach-Zender modulation, frequency-locked subcarrier laser) will be investigated if the results of the high power testing warrant this approach.



4.2. Mode Cleaner

The design parameters of the mode cleaner depends on the specific Advanced LIGO IFO requirements and to some extent on the constraints imposed by the vacuum system. These exact parameters will not necessarily be adopted in the Advanced LIGO IO. Rather, they represent a general design philosophy and can be used for establishing performance limits. Detailed calculations are presented in Appendix 1. Mode cleaner parameters are listed in Table 1.

It is important to keep in mind that there are trade offs among design parameters. For example, the jitter suppression can be enhanced by increasing the mode cleaner finesse; however, this comes with the penalties of increased radiation pressure and thermal loading of the cavity.

Table 1: Advanced LIGO Mode Cleaner Parameters

Parameter	*Value*
Mode Cleaner Length	16.6551 m
Free spectral range	9.000 MHz
Mirror Dimensions	20 cm diameter 10 cm thick
MC Flat mirror reflectivity (intensity)	0.9985
MC Curved Mirror Reflectivity (intensity)	0.9999
Assumed mirror losses	15 ppm
Finesse	2026
MC curved mirror RC	28.00 m
Cavity *g* factor	0.407
Transmission $TEM_{01/10}$ modes	1 ppm
Max HO mode Transmission	1.5 ppm
Waist size	2.7 mm
Stored Power	97 kW
Intensity at flat mirrors	410 kw/cm^2
Transmittance	97%

4.2.1. Changes in the vacuum envelope

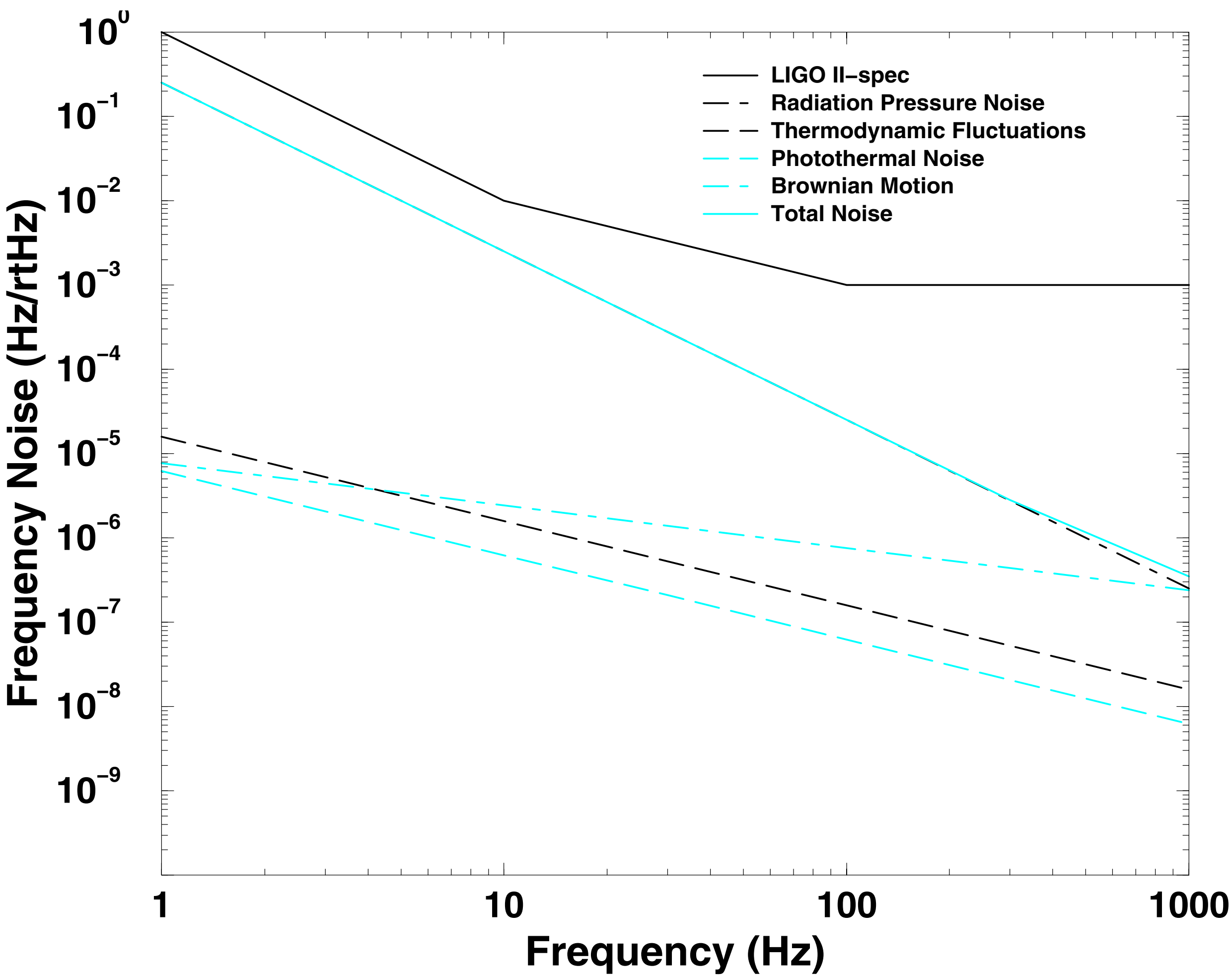
The combination of increased laser power, larger mode-cleaner finesse, and more stringent low-frequency noise requirements mean that small (7.5 cm diameter) optics cannot be used in Advanced LIGO. The reference design thus uses 20 cm diameter mirrors in GEO 600 suspensions.[1] A preliminary AutoCAD layout was performed to verify that the MC and MMT3 optics fit in the HAMs. The suspension footprint (25.7 cm wide; 28.6 cm deep) fits on the HAM table (as does the MMT3 suspension), but the beams cannot all be fit in the 77 cm diameter tube linking HAMs 1 and 2.   We note that the MC curved mirror (MC2 in LIGO 1) will sit on HAM 3 in the Advanced LIGO IO layout.

- ***A minimum of 125 cm diameter clear aperture between the chambers is needed.***

1. LIGO II Suspensions: Reference Design, T2000012

4.2.2. Mode Cleaner Performance

4.2.2.1 Frequency Noise



The figure above shows the frequency fluctuations of the field due to displacement fluctuations in the mode cleaner for various noise sources discussed in the Appendix (taken as the quadratic sum of all the noise sources) for 20 cm diameter by 10 cm thick fused silica mirrors. Small (7.5 cm diameter) mirrors suffer from severe excess radiation pressure noise at low frequencies and will not work for Advanced LIGO. In addition, the figure shows the current Advanced LIGO specification for the frequency noise (10^{-2} Hz/Hz$^{1/2}$ at 10 Hz falling as $1/f$ to 10^{-3} Hz/Hz$^{1/2}$ at 100 Hz and an assumed $1/f^2$ increase below 10 Hz).

Note: This calculation should not be taken too seriously at frequencies above the corner frequency of the arm cavities (180 Hz). We do not know yet how the noise in that frequency region affects the signal. It will most likely not be dominated by the frequency noise in the input light, but rather by the shot noise limit of the main interferometer.

From these plots, several features are apparent:

- Radiation pressure from input fluctuations in the PSL beam dominates at low frequencies.
- A 16.6 m length MC easily meets the technical noise requirements for Advanced LIGO at all frequencies above 10 Hz.

4.2.2.2 Jitter Suppression

Jitter suppression is governed by the finesse of the mode cleaner (greater finesse provides more suppression) and by the g-factor of the mode cleaner cavity (which determines the relative amplitudes of the transmitted modes). Jitter is suppressed by a factor of approximately 2000 in this design. (See appendix 1.2) Assuming an input jitter of 4 x $10^{-6}/Hz^{1/2}$, the output jitter is ~ 2-3 times above that required by Advanced LIGO.

- Increasing the cavity finesse can increase the suppression factor at the expense of increased radiation pressure; given displacement noise constraints, active stabilization of the input beam may be required.

4.2.2.3 Thermal Distortions

Assuming 2 W absorbed power in the coatings (90 kW stored power; 1 ppm absorption), simple estimates[1] for the deformation give the following:

4.2.2.3.1 Fused Silica

The sagitta s will change in each mirror by δs ~ 5.6 nm. This will change the effect radii of curvatures of the mirrors. In the short mode cleaner, the radii of the flat mirrors will be greater than 600 m, the radius of the curved mirror might change from 43 to 44 m. In the long mode cleaner, the radii of the flat mirrors will be above -3500 m, the curved mirror changes from 254 m to 264 m. All these changes are sufficiently small that they can be included in the final design.

4.2.2.3.2 Modal distortion

The small changes in the eigenmode of the mode cleaner (2%-range) suggest that the distortions will be well below 0.05%.

4.2.2.3.3 MELODY Modeling

The most recent version of MELODY has been updated to include non-normal incidence mirrors and triangular cavities. Preliminary runs were performed using an optimized MC length of 16.655 m. Some results:

- The MC flat mirrors see an elliptical beam profile owing to the the 45 deg. angle of incidence. Melody predicts a radius of curvature change to 280 m (out-of-plane) and 680 m (in-plane). These correspond to sagitta of 7.1 nm (out-of-plane) and 2.9 nm (in-plane).
- The MC cavity is stable at full power with g=0.504
- The amount of 20 mode contamination after the MC is 0.1% and is correctible by MMT adjustment.
- No difference seen between sidebands (on resonance) and carrier.

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1. W. Winkler, et al., Phys. Rev. A44, 7022 (1991).

- Detuning the 180 MHz sideband by 1 KHz (big!) results in 18% decrease in sideband transmission (as expected), but also results in a 3% power asymmetry between upper and lower sideband.

4.2.2.4 Mode Cleaner Alignment

Input jitter on the PSL light will couple to misalignments in the mode cleaner to produce excess frequency noise.[1] Requiring that this noise be less than the MC frequency noise requirement at 100 Hz leads to:

- $\theta_{rms} < 1.3 \times 10^{-7}$ rad

See Appendix 1.3.

4.2.2.5 RFAM from sideband detuning

TBD pending analysis of requirements of RFAM on DC offset locking.

4.3. Mode Matching Telescope

The design for the Advanced LIGO MMT will closely follow the LIGO I design. Three mirrors (two 7.5 cm diameter mirrors in small optics suspensions and one 25 to 29 cm diameter mirror in a large optics suspension) will be used to mode match the laser from the mode cleaner to the interferometer.

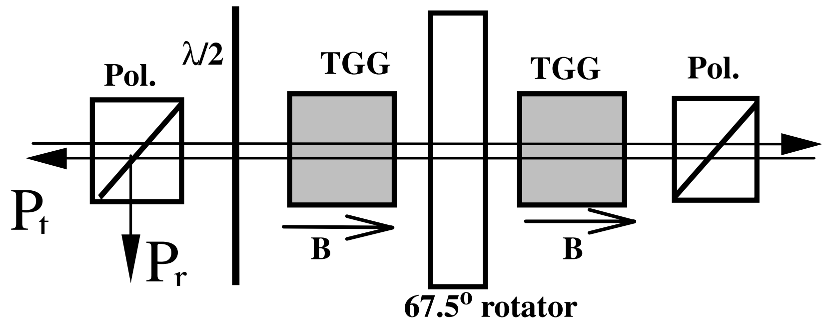
We anticipate very little technical risk associated with this design.

4.4. Faraday Isolator

The power increase in Advanced LIGO will cause increased thermal lensing and thermally-induced birefringence in the Faraday isolator. Excessive thermal lensing could potentially introduce uncompensatible higher order modes; the magnitude of these modes determines the placement of the FI (before or after the MC). Excessive thermal birefringence leads to decreased optical isolation.

1. Misalignment - Beam Jitter Coupling in LIGO, LIGO-T960120-00-D

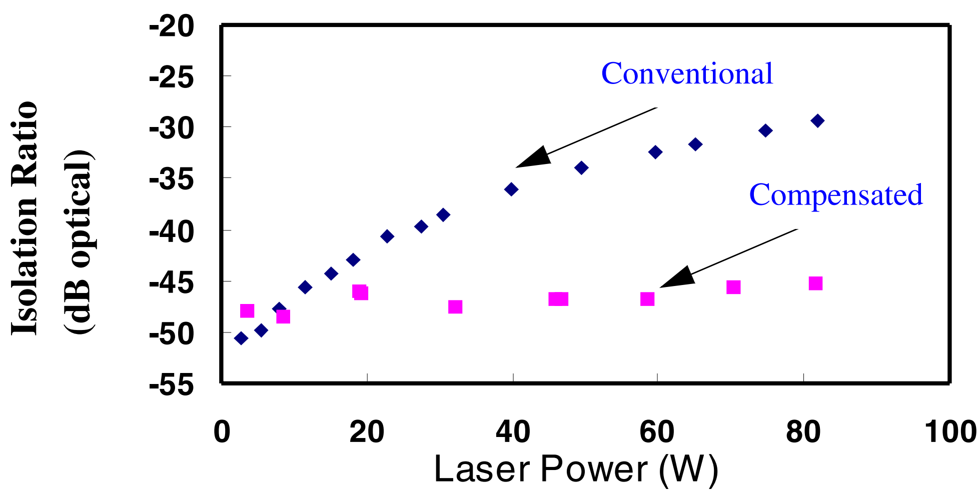
4.4.1. High Power Isolator Design



The optical isolator design above has been tested as a prototype for Advanced LIGO.[1] In this design, two 22.5° Faraday rotators and a reciprocal quartz polarization rotator placed between them replace the traditional single crystal 45° Faraday rotator. In such a configuration, polarization distortions which a beam experiences while passing the first rotator, will be partially compensated in the second.

4.4.2. Isolation Performance

This device has been tested at powers up to 85 W (double pass). The results (shown below) are quite promising. We were able to achieve an isolation ratio of 45 dB over the 0-85 W range.



1. Suppression of Self-Induced Depolarization of High-Power Laser Radiation in Glass-Based Faraday Isolators, E. Khazanov, et al., J. Opt. Soc. Am B. 17, 99-102 (2000).

4.4.3. Isolator Thermal Lensing

Three different TGG-crystals were tested at powers of 50 W and beam sizes of 1 mm. The results are shown in table2.

Table 2: Thermal Lensing in TGG

Crystal	*length*	*horizontal thermal focal length*	*vertical thermal focal length*
Litton	20mm	5700mm	3800mm
EOT	19mm	4800mm	5900mm
Russia	10mm	7400mm	10000mm
Error bar +/- 2000 mm			

As the focal lenses are still larger than the Rayleigh range of the 50 W laser used for the measurements, the changes in the mode were small. That also limits the accuracy of the measurement. The differences between the horizontal and the vertical values are within the errorbars of the measurement.

As the thermal lens scales with the inverse power, a factor 3 in power would therefor mean a factor 1/3 in focal length. The resulting 2m lens can be included in the mode matching calculation. The more severe problem of the non compensable higher order modes can be estimated with MELODY. We estimate a non compensable amount of higher order modes in the vicinity of or below 1% for a 150W beam of 1mm beam size. An experimental verification is part of the research program at the University of Florida.

4.4.4. Isolator Location

The reference design has a fixed in-vacuum isolator located between the mode cleaner and the mode-matching telescope. This location has several drawbacks: (1) Optical distortions induced by the isolator are not removed before the light reaches the core optics. (2) Vibrations of the HAM table can impose noise on the light. (3) Alignment is difficult. (4) The magnet is composed of materials that could compromise vacuum quality.

All of these factors suggest that the Faraday might better be located *before* the mode cleaner and on the PSL/IOO table, before the beam enters the vacuum system. We leave this TBD at present.

4.4.5. Isolator Suspension

TBD pending above analysis.

APPENDIX 1 MODE CLEANER NOISE SOURCES

1.1. Displacement Noise in The Mode Cleaner

Length fluctuations of the mode cleaner will compromise the frequency stability of the field leaving the mode cleaner. Here, we describe noise sources in a Advanced LIGO mode cleaner giving displacement noise of the mirrors.

1.1.1. Radiation Pressure Noise

The force created by the radiation pressure is proportional to the power P impinging on the mirror and the angle of incidence φ.

$$F = 2\cos\varphi\frac{P}{c}$$

Fluctuations in the power thus lead to fluctuations in force and, consequently, fluctuations in the position of the suspended mirror.

The limit for the power fluctuations of coherent (non squeezed) light sources is given by Poissonian statistics (equivalent to shot noise) and is one part of the standard quantum limit. However, power fluctuations of the field in the mode cleaner will not be suppressed to the fundamental shot noise limit. The Advanced LIGO power fluctuations are assumed to be between 10^{-8} - 10^{-9} /Hz$^{1/2}$, resulting in a mirror displacement that depends on the noise frequency of the power fluctuations and the transfer function $\chi(\omega)$ of the system. For a suspended mirror of mass m, the spectral density of the displacement noise is:

$$S_R(\omega) = |\chi(\omega)|^2 4\frac{(\sin\varphi)^2}{c^2m^2}S_P(\omega)$$

where $S_P(\omega)$ is the spectral density of the power fluctuations in [W^2/Hz].

The transfer function of the suspended mirror (a harmonic oscillator) is

$$|\chi(\omega)| = \left|\frac{1}{\omega_o^2 - \omega^2 - i\gamma\omega}\right|$$

where γ is the damping and ω_o is the resonance frequency of the pendulum.

As the resonance frequency and the damping are much smaller than the in-band noise frequencies, we find:

$$S_R(\omega) = \frac{1}{4}\frac{1}{\pi^4}\frac{(\sin\varphi)^2}{c^2m^2}\frac{1}{f^4}S_P(\omega)$$

When typical numbers are put in, this becomes:

$$S_R(f) = 2.85\times10^{-28}\frac{\mathrm{m}^2}{\mathrm{Hz}}\left(\frac{\mathrm{kg}}{m}\right)^2\left(\frac{dP}{P\times10^{-9}}\right)^2\left(\frac{P}{100\mathrm{kW}}\right)^2\left(\frac{\mathrm{Hz}}{f}\right)^4(\sin\varphi)^2$$

In a ring cavity, the power fluctuations are similar on each mirror, therefore the displacement noise is correlated. The angle of incidence on two of the three mirrors is 45^{o}, so the force is only $1/(\sqrt{2})$ of the normal incidence force. However, the displacement takes place also at 45^{o} relative to the incident beam, causing a change in the optical path length of $\sqrt{2}$ of the displacement of the mirror. The change in the optical pathlength at one of the 45^{o} mirrors is thus:

$$dx_{45^o}(f) = \sqrt{2.85\times10^{-28}}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\left(\frac{\mathrm{kg}}{m}\right)\left(\frac{dP}{P\times10^{-9}}\right)\left(\frac{P}{100\mathrm{kW}}\right)\left(\frac{\mathrm{Hz}}{f}\right)^2\sqrt{\frac{2}{2}}$$

The normal incidence mirror sees the full displacement of $\sqrt{2.85\times10^{-28}}$ m/Hz$^{1/2}$, but because the light has to travel to and away from the mirror, the roundtrip length changes by 2 times this displacement. The total change in the roundtrip length is:

$$dx_{rad}(f) = \sqrt{2.85\times10^{-28}}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\left(\frac{\mathrm{kg}}{m}\right)\left(\frac{dP}{P\times10^{-9}}\right)\left(\frac{P}{100\mathrm{kW}}\right)\left(\frac{\mathrm{Hz}}{f}\right)^2(2+2)$$

Note that this is not the distance between focus and curved mirror, but the total roundtrip.) The first 2 is for the fact that we have two 45deg mirrors, the second takes care of the fact that the light at the curved mirror sees the displacement twice.

$$dx_{rad}(f) = 6.75\times10^{-14}\frac{\mathrm{m}}{\sqrt{Hz}}\left(\frac{\mathrm{kg}}{m}\right)\left(\frac{dP}{P\times10^{-9}}\right)\left(\frac{P}{100\mathrm{kW}}\right)\left(\frac{\mathrm{Hz}}{f}\right)^2$$

1.1.2. Thermal noise

Thermal noise is computed from Braginsky et al,[1] again keeping in mind that the displacement of the 45^o mirrors causes a $\sqrt{2}$ longer change in the optical pathlength at each mirror, while the optical pathlength at the curved mirror changes twice the displacement.

$$dx_{thermal}(f) = \sqrt{2(\sqrt{S_f(f)}\sqrt{2})^2 + (2\sqrt{S_c(f)})^2}$$

The first term under the root is the optical path length change at the flat mirror times 2 for the 2 mirrors. The last part is the path length change at the curved mirror. These 2 spectral densities will be different because of different beam sizes.

1.1.3. Thermodynamic Fluctuations

Thermal fluctuation noise is calculated from

$$S_{TDF}(\omega) = \frac{8}{\sqrt{2\pi}}\alpha^2(1+\sigma)^2\frac{kT^2}{\rho C}\frac{a^2}{r^3}\frac{1}{4\pi^2 f^2}$$

where Table 3 defines and gives values for most of the parameters, and

$$a^2 = \frac{\kappa}{\rho C}$$

Table 3: Parameters of Sapphire and fused Silica

	fused Silica
Thermal Expansion: α[1/K]	5.5 e-7
Poissons ratio: σ	0.17
Density: ρ [kg/m^3]	2200
Specific heat capacity: C [J/kg K]	670
Thermal conductivity: κ [J/smK]	1.4
Youngs modulus: *E* [J/m^2]	7.2e10
Loss Angle: Φ	5e-8

1. Thermodynamic Fluctuations and Photo-thermal Shot Noise in Gravitational Wave Antennae, V. Braginksy, et al., Phys. Lett. A264, 1 (1999).

The value for fused Silica and a beam size r_o of 2 mm is:

$$S_{TDF}(f) = 3.35\times10^{-36}\left(\frac{\text{m}^2}{\text{Hz}}\right)\left(\frac{2\text{mm}}{r_o}\right)^3\left(\frac{\text{Hz}}{f}\right)^2$$

The value for Sapphire and a beam size r_o of 2 mm is:

$$S_{TDF}(f) = 2.1\times10^{-33}\left(\frac{\text{m}^2}{\text{Hz}}\right)\left(\frac{2\text{mm}}{r_o}\right)^3\left(\frac{\text{Hz}}{f}\right)^2$$

This noise is independent with respect to the incoming laser power, except that the absorption leads to an increase in the temperature of the substrate. This increase is probably insignificant.

There is one assumption used in Braginsky's calculations:

$$2\pi f \ll \frac{a^2}{r_o^2}$$

Fused silica has an a=1 mm/$\sqrt{s}$ and Sapphire has a=3.6 mm/$\sqrt{s}$. Fused silica meets the requirements everywhere above the pendulum frequency. In contrast, for sapphire there is a problem with this assumption at low frequencies.

1.1.4. Photothermal Noise

Photothermal noise varies as

$$S_{PT}(\omega) = 2\alpha^2(1+\sigma)^2\frac{h\upsilon P_o}{(\rho C\pi r_o^2)^2}\frac{1}{4\pi^2 f^2}$$

Here, P_o is the absorbed power. The absorption is assumed to be 1 ppm at each surface. The transmitted power behind the mode cleaner is expected to be around 135 W. The cavity internal power is therefor this 135 W divided by the power transmission of the MC-mirror. If we assume a finesse of 2000 or a T=0.15% we find P_c=90 kW power circulating in the MC. Roughly 100 mW is absorbed in each mirror.

For fused silica mirror substrates we find:

$$S_{PT}(f) = 1.2\times10^{-36}\left(\frac{\text{m}^2}{\text{Hz}}\right)\left(\frac{P_o}{100\text{mW}}\right)\left(\frac{2\text{mm}}{r_o}\right)^4\left(\frac{\text{Hz}}{f}\right)^2$$

For sapphire substrates we find:

$$S_{PT}(f) = 2.5\times10^{-35}\left(\frac{\text{m}^2}{\text{Hz}}\right)\left(\frac{P_o}{100\text{mW}}\right)\left(\frac{2\text{mm}}{r_o}\right)^4\left(\frac{\text{Hz}}{f}\right)^2$$

1.1.5. Brownian motion or structural damping

Brownian motion introduces the following noise:

$$S_{PT}(f) = \frac{4kT}{2\pi}\frac{(1-\sigma^2)}{Er_o\sqrt{2\pi}}\Phi\frac{1}{f}$$

For fused silica we find:

$$S_{PT}(f) = 3.5\times10^{-37}\left(\frac{\mathrm{m}^2}{\mathrm{Hz}}\right)\left(\frac{2\mathrm{mm}}{r_o}\right)\left(\frac{\mathrm{Hz}}{f}\right)$$

For Sapphire we find:

$$S_{PT}(f) = 3.6\times10^{-39}\left(\frac{\mathrm{m}^2}{\mathrm{Hz}}\right)\left(\frac{2\mathrm{mm}}{r_o}\right)\left(\frac{\mathrm{Hz}}{f}\right)^2$$

1.1.6. Summary

The spectral densities of the displacement caused by the various noise sources are derived for a single mirror only and a specific set of parameters. The mode cleaner will consist of three mirrors in a ring cavity. Two of these mirrors will be flat and the angle of incidence will be very close to 45 degrees. The third mirror will be curved and hit under normal incidence. The two different configurations discussed here have different lengths, different radii of curvatures, and different finesses. These parameters will affect the displacement noise and the subsequent frequency noise of the laser field due to the change of the stored power and the change in the beam size. In addition, we take into account that the maximum mass for a fused silica mirror is 7 kg.

These length fluctuations are converted into frequency noise in the field leaving the mode cleaner. That conversion depends on the free spectral range of the mode cleaner and in principle on the locking scheme. We assume here, that the laser follows the mode cleaner length, that we have a feedback loop with infinite gain locking the laser frequency to the mode cleaner.

$$d\upsilon = FSR\frac{dL}{\lambda}$$

For the short mode cleaner we find:

$$d\upsilon = 5.65\times10^{-6}\frac{dL}{10^{-18}}$$

For the long mode cleaner we find:

$$d\upsilon = 1.41\times10^{-6}\frac{dL}{10^{-18}}$$

The resulting frequency noise spectrum is shown in the main text.

1.2. Jitter suppression

Beam jitter (frequency dependent angular and lateral deviations of the beam) may be viewed as the superposition of higher-order Gaussian modes on the TEM_{00} mode.[1] Because higher-order modes are suppressed by the mode cleaner, jitter is suppressed by the mode cleaner. The amplitude of the beam wiggle is suppressed by:

$$S_{mn} = \frac{1}{\left[1+\left\{\frac{2F}{\pi}\sin[(m+n)\operatorname{acos}(\sqrt{g})]\right\}^2\right]^{\frac{1}{2}}}$$

1.3. Mode Cleaner Alignment Tolerance

We consider the misaligned mode cleaner. Using the formalism of Hefetz,[2] we compute the reflected cavity field,

$$E_r = r_1\left[I-\frac{P_{rt}}{r_1^2}\right](I-P_{rt})^{-1}E_0$$

where E_r, E_i are two-component vectors representing the TEM_{00} and TEM_{01} modes of the reflected and input beams, I is the identity matrix and $P_{rt} = (r_1\, P\, r_2\, P\, M_2)$ is the round trip cavity propagator, with P the one way propagator. M_2 is the misalignment matrix of mirror 2,

$$M_2 = \begin{bmatrix} 1 & -2i\Theta \\ -2i\Theta & 1 \end{bmatrix}$$

where $\Theta = \theta\pi\frac{w_0}{\lambda}$ and θ is the angle of misalignment of mirror 2.

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1. *Do wiggle effects depend on mode cleaner length,* A. Abramovici et al, LIGO Technical Note #20 (1988).; *Optical mode cleaner with suspended mirrors,* A. Araya *et al.*, Appl. Opt. **39**, 1446 (1977).

2. *Principles of Calculating Alignment Signals in Complex Resonant Optical Interferometers*, Y. Hefetz, N. Mavalvala, D. Sigg, pg. 9

The above expression for the reflected field gives:

$E_{r0} \sim i\ \Theta\ E_{i1} = i\ \Theta\ \varepsilon\ E_{i0}\ e^{i\omega t}$ where ε is the ratio of the amplitude of the TEM_{00} and TEM_{01} modes on the incident light. This complex time-varying term is seen as frequency noise at the photodetector.

We compare the above noise to the thermal noise limit of the mode cleaner frequency stability, using dν ~ 1 x 10^{-5} Hz / $Hz^{1/2}$ at f = 100 Hz. The signal from the frequency noise is

$$E_{r0} = E_{io} \frac{2 \cdot 2\pi \cdot d\nu}{c(1 - r^2)} L$$

Setting this expression equal to the previous equation from beam jitter and solving for θ, we obtain.

$$\theta = \frac{24\ d\nu}{\nu\ (1 - r^2)} \frac{1}{w_0 \varepsilon_1}$$