Designs of the frequency reference cavity for the AEI 10 m Prototype interferometer

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Designs of the frequency reference cavity for the AEI 10 m Prototype Interferometer

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Abstract. The AEI 10 m Prototype is in its designing phase and will provide a test-bed for very sensitive interferometric experiments, such as the sub-SQL interferometer. It will test new techniques to reach – and even surpass – the Standard Quantum Limit. The experience and knowledge that can be gained from this experiment can be applied to large-scale interferometric gravitational detectors to improve the detector sensitivities. In order for the sub-SQL interferometer to achieve the required sensitivity all limiting noise sources need to be suppressed sufficiently. Noise sources can include seismic noise, thermal noise, and laser noise; laser frequency noise will be the main focus of this document. The laser frequency noise will be suppressed to a level of $10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 20 Hz dropping to below $10^{-6}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 1 kHz. The proposed design to suppress the laser frequency noise with a ring cavity is described in this paper.

1. Introduction

The second generation of interferometric gravitational wave detectors such as Advanced LIGO[1], Advanced VIRGO[2], LCGT[3], and GEO HF[4], have been proposed, and research and design work has been started. The design upgrade will enable the sensitivity of these detectors to approach the Standard Quantum Limit (SQL). However, studies and research on SQL with prototype interferometers is necessary to fully understand new techniques to reach and surpass the limit, as well as to obtain experience that can be applied to large-scale detectors.

The AEI 10 m Prototype project began in 2005 with the aim of providing a test-bed for very sensitive interferometric experiments. One of these is the sub-SQL interferometer, which is in the initial designing phase. It aims to reach and go beyond the SQL with a Fabry-Pérot Michelson interferometer. In order to realize this goal, all the classical noise sources must be suppressed well below the SQL level at the frequencies of interest($\sim$ 20 Hz to 1 kHz). Laser frequency noise would deteriorate the sensitivity if not suppressed properly. The AEI Prototype will use a laser frequency stabilization system composed of a high-finesse triangular cavity (called 'the reference cavity' throughout this document). The sub-SQL interferometer will use Fabry-Pérot cavities with very light-weight (100 g) mirrors which are susceptible to radiation pressure noise, hence, the arm cavities do not provide a good frequency reference. In the following sections, the current design of the laser frequency stabilization system is described.

2. Laser frequency stabilization system

The mirrors of the reference cavity are suspended from a triple pendulum system. It will be placed on optical tables whose relative positions are controlled by a Suspension Platform Interferometer [5], inside the vacuum tanks, and will provide a frequency stabilized laser to the Sub-SQL interferometer input.

2.1. Sensitivity goal

In order to reach the SQL all the classical noise sources need to be suppressed so that their levels are well below that of the SQL. In the experiment the designed sum of all the classical noise sources is below the SQL level by about a factor of 2 to 4, ranging from $\sim 50\,\text{Hz}$ to $\sim 400\,\text{Hz}$. With the assumed common-mode rejection ratio of 1 %, this sets the maximum allowable level of the frequency noise in the input beam to the interferometer to be $10^{-3}\,\text{Hz}/\sqrt{\text{Hz}}$ at 20 Hz dropping to below $10^{-5}\,\text{Hz}/\sqrt{\text{Hz}}$ at 1 kHz. This corresponds to a reference-cavity length-noise of 10^{-16} to $< 10^{-18}\,\text{m}/\sqrt{\text{Hz}}$, from $\sim 20\,\text{Hz}$ to 1 kHz. Therefore the laser frequency stabilization system must stabilize the laser frequency down to this level. This maximum allowable noise level is shown in Fig. 1, along with the target for the noise, which includes a safety margin (i.e. its level is an order of magnitude lower than the maximum). The noise level is calculated with carefully chosen suspension design parameters as well as optical design parameters.

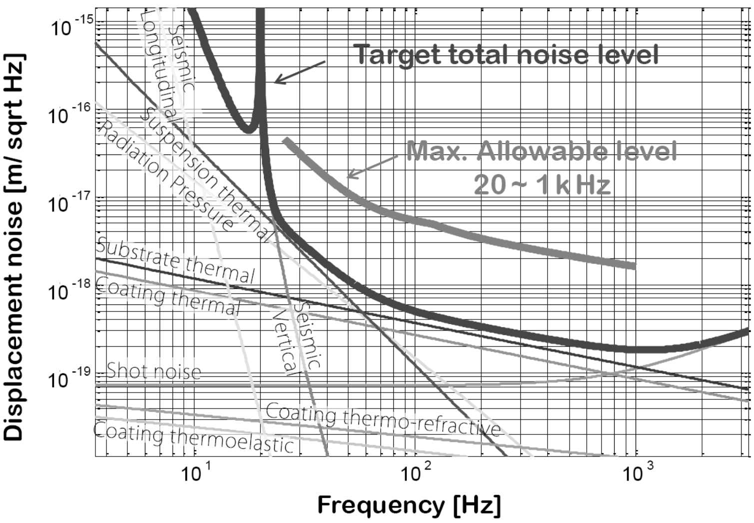

Figure 1. Required frequency stabilization level expressed in terms of equivalent displacement noise.

2.2. Suspension design

The mirrors for the frequency reference cavity must be sufficiently seismically isolated, as their residual motion sets limits on the achievable laser frequency stability, as shown in Fig. 1.

The measured seismic noise in the laboratory is approximately $10^{-7}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 1 Hz, scaling with f^{-2} at higher frequencies; while the required noise performance is better than $\sim 10^{-18}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 50 Hz.

To reduce the contribution from seismic noise, all optics are first placed on an optical table that also functions as a passive pre-isolation stage. This table is based on the HAM-SAS (Horizontal Access Module - Seismic Attenuation System) table [6, 7] developed for Advanced LIGO, and above several Hz will provide at least 60 dB and 70 dB attenuation in horizontal and vertical directions, respectively.

Additional seismic isolation is required to meet the design goal however. The mirrors are further isolated by a triple-stage suspension system – suspended from a rigid enclosure constructed from extruded aluminium struts – with the mirror comprising the final pendulum mass. The stage directly above the mirror is an aluminium cylinder of the same mass and outer dimensions. The uppermost stage is a rectangular piece, designed to hold combined position sensing, eddy-current damping and position feedback assemblies – used to align the suspension system and damp the main pendulum modes, over six degrees of freedom.

To alleviate any coupling from vertical to horizontal seismic motion, the wires suspending the upper mass from the suspension enclosure, and those suspending the intermediate mass from the upper mass, are further isolated by attaching them to maraging steel cantilever blades. This results in a combined spring system more compliant in the vertical direction than the wires alone, thus lowering the vertical resonant frequencies.

In order to reduce the thermal noise contribution from the suspension system, the suspension elements are high carbon-content stainless-steel wires with a high breaking stress and relatively low mechanical loss. The wires holding the mirror mass will be extremely thin (28 μm radius) thus keeping the wire's vertical bounce mode as low as possible ($\sim$ 20 Hz) and the first lateral violin resonance as high as possible ($>$ 400Hz) while still loading the wire to less than a third of the breaking point.

The modelled seismic and thermal noise spectra for the reference cavity suspension systems can be seen in Fig. 2.

2.3. Optical design

The residual cavity length fluctuations cause frequency fluctuations in the output beam with an amplitude inversely proportional to the cavity length. Therefore it is beneficial to have a long cavity length, and the design utilizes two optical tables which are separated by $\sim$ 11 m in such a way that two mirrors (input and output couplers) will be placed on one table, and the curved end mirror will be placed on the other table.

The circulating power is optimized so that the radiation pressure noise and shot noise are well below the required noise level, with the mirror mass being fixed to be 850 g due to load/space restrictions for the optical tables. The input power and finesse are optimized to meet the circulating power restriction, and to optimize the shot noise limited performance.

The cavity needs to be non-degenerate because higher order spatial-mode contents will disturb the auto-alignment signals. Assuming there will be $\sim$ 5 % of higher order spatial-mode contributions in the input beam, it is sufficient to suppress them by a factor of $\sim$ 1000 by using the cavity. A beam waist size (the waist is located between the two couplers) of 2.4 mm is large enough such that the coating Brownian thermal noise (with its linear spectral density being inversely proportional to the beam size) contribution is small enough. Simultaneously, it is small enough that the optically induced torque, as well as the power fluctuation due to angular fluctuation, are negligible. The cavity g-factor (which provides an indication of the optical stability; here, the condition of $0 < \mathrm{g} < 1$ means the reference cavity is optically stable) is calculated to be 0.67 to best suit the beam size and the cavity length.

The design parameters are summarized in Table 1.

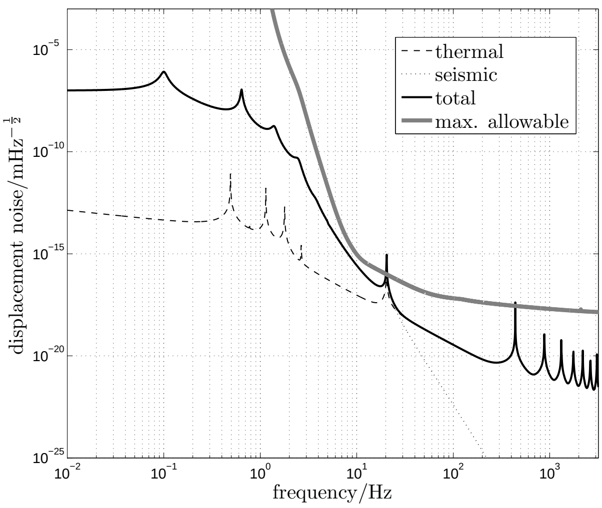

Figure 2. Simulated noise performance of the reference cavity mirror suspensions. The total noise from both seismic and thermal contributions is seen to be less than the frequency reference maximum allowable level at all points, except those where the wire vertical and lateral violin resonances lie.

Table 1. Optical design.

Round trip length	24.6 m
Input power	0.133 W
Finesse	7305
Circulating power	232 W
Higher order spatial-mode suppression	>1000
Cavity g-factor	0.67
Beam waist size	2.43 mm

2.4. Control of the system

In principle the laser frequency needs to be stabilized in the frequency range of interest, although in reality frequency noise at other frequencies could also couple into the target frequency region and deteriorate the performance of the system. Thus, control must be implemented over all the relevant frequency regions. The following frequency stabilization scheme utilizes three components; the main laser, the reference cavity, and the auxiliary laser. The main laser is a 2 W InnoLight Mephisto non-planar monolithic ring oscillator (NPRO), which is amplified by a four head Nd:YVO_4 laser amplifier to a power level of 35 W.

Below ~ 4 Hz, the iodine line stabilized Nd:YAG auxiliary laser (iodine laser from here on), used for the Suspension Platform Interferometer provides a better frequency reference than the reference cavity eigenmode, with its frequency noise at a level of $50\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ between ~ 0.5 Hz to $\sim$4 Hz, increasing very roughly with $f^{-0.62}$ when going from ~ 0.5 Hz to 10^{-4} Hz. Above ~ 4 Hz the cavity eigenmode will provide the most stable frequency reference. Therefore below ~ 4 Hz, the eigenmode of the reference cavity is controlled via a coil-magnet actuator system to follow the iodine laser frequency while the NPRO is controlled to follow the cavity eigenmode from DC to several tens of kHz via temperature control loop, piezoelectric transducer control loop, and a phase-correcting pockels cell loop. An open loop gain of $\sim 10^7$ is required above 20 Hz. A Pound-Drever-Hall (PDH) scheme is used for the control. The control topology is sketched in Fig. 3. The 35 W main laser is split into two beams. One of them is phase modulated with an Electro-optic Modulator (EOM) to create phase modulation sidebands at a modulation frequency of 8 MHz, which do not resonate inside the reference cavity. A control signal is applied to the main laser, and to a phase corrector EOM. The other beam is coupled with the iodine laser that is phase modulated with an Acousto-optic modulator (AOM). A control signal is applied to the coil-magnet actuator of one of the mirrors of the frequency reference cavity. The figure does not include the auto-alignment system, which also uses the same modulation sidebands created by the EOM to align the reference cavity. The control parameters are shown in Table 2. The modulation index is optimized for the shot noise performance of the reference cavity.

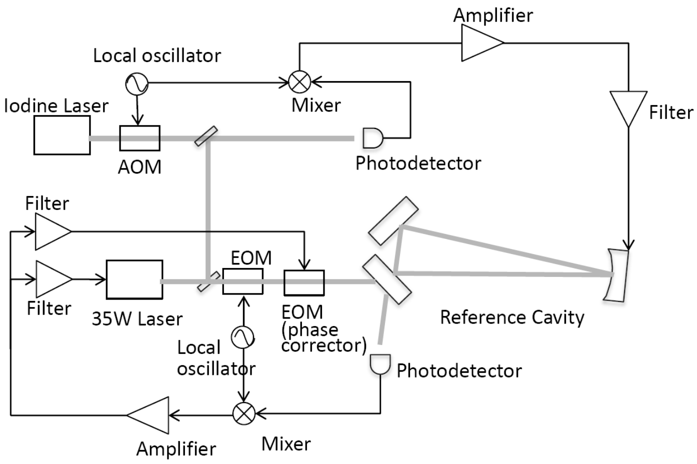

Figure 3. Control topology. It consists of two control loops. One is for controlling the frequency of the beam that goes into the reference cavity from DC to several tens of kHz, with its reference being the eigenmode of the reference cavity. The feedback signal is applied to the 35 W main laser and to the phase corrector EOM at lower and higher frequencies, respectively. The second loop is for controlling the length of the reference cavity below ~ 4 Hz to follow the frequency of the iodine laser.

Table 2. Control parameters.

Cavity FSR	12.1867 MHz
Modulation frequency	8 MHz
Modulation index	0.6

3. Summary

The laser frequency stabilization system is required for the successful operation of the sub-SQL interferometer. The system will utilize a high-finesse optical cavity with suspended mirrors of which the suspension design, the optical design, and the control design have been developed.

With the frequency stabilization system the laser frequency noise will be suppressed to a level of $10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 20 Hz dropping to below $10^{-6}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 1 kHz.

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