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The AEI 10 m prototype interferometer

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Abstract

A 10 m prototype interferometer facility is currently being set up at the AEI in Hannover, Germany. The prototype interferometer will be housed inside a 100 m^3 ultra-high vacuum envelope. Seismically isolated optical tables inside the vacuum system will be interferometrically interconnected via a suspension platform interferometer. Advanced isolation techniques will be used, such as inverted pendulums and geometrical anti-spring filters in combination with multiple-cascaded pendulum suspensions, containing an all-silica monolithic last stage. The light source is a 35 W Nd:YAG laser, geometrically filtered by passing it through a photonic crystal fibre and a rigid pre-modecleaner cavity. Laser frequency stabilisation will be achieved with the aid of a high finesse suspended reference cavity in conjunction with a molecular iodine reference. Coating thermal noise will be reduced by the use of Khalili cavities as compound end mirrors. Data acquisition and control of the experiments is based on the AdvLIGO digital control and data system. The aim of the project is to test advanced techniques for GEO 600 as well as to conduct experiments in macroscopic quantum mechanics. Reaching standard quantum-limit sensitivity for an interferometer with 100 g mirrors and subsequently breaching this limit, features most prominently among these experiments. In this paper we present the layout and current status of the AEI 10 m Prototype Interferometer project.

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(Some figures in this article are in colour only in the electronic version)

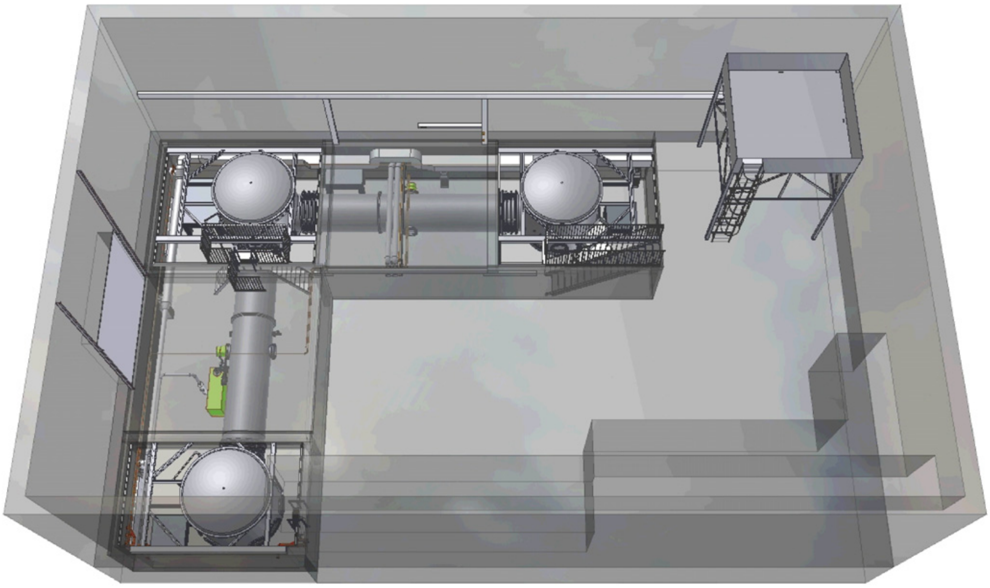

Figure 1. The vacuum system is set up in the downstairs area of the AEI prototype hall. The upstairs area is used for assembly of mechanical components before installation as well as for other optical experiments.

1. Introduction

In the AEI 10 m prototype interferometer facility we will test and develop advanced techniques that have the potential to be used for future upgrades to GEO-HF [1]. Among these are the digital control and data system, and high-power laser systems. A second goal is to provide training for scientists who will install these techniques in GEO-HF and operate that gravitational-wave observatory.

However, the 10 m prototype facility will also host experiments in their own rights. We have designed the main instrument, a Michelson interferometer, such that it will be capable of reaching a sensitivity effectively limited by quantum noise in the measurement band. Photon shot noise and quantum back-action noise at the interferometer mirrors will be the dominant noise sources in a band around 100 Hz. This sensitivity is referred to as the standard quantum-limit (SQL). Reaching or even surpassing the SQL for an interferometric measurement is a long-standing goal in precision metrology [2–4]. With the setup described in this paper we will tackle this challenge with macroscopic test masses of 100 g each. Once the SQL is reached, various techniques, such as squeezed-light input, can be leveraged towards achieving sub-SQL sensitivity.

2. Vacuum system

The vacuum system for the AEI 10 m prototype consists of three tanks with a diameter of 3 m and a height of 3.4 m, separated by 11.65 m. The tanks are connected by 1.5 m diameter beam tubes. There are no gate valves to shut off certain sections of the vacuum system. Overall, the vacuum system encloses about 100 m^3. It is designed such that it fits neatly into the existing lab facilities (see figure 1). For the roughing, a screw pump with a pump rate of 170 l s^{-1} at atmospheric pressure is attached to one of the tubes. Two magnetically levitated turbo-molecular pumps with a pumping speed of 2000 l s^{-1} each, backed by a single scroll pump, evacuate the system to 10^{-6} hPa within 12 h. After about 1 week of pumping, a pressure of 10^{-7} hPa is reached. The residual gas pressure is dominated by water vapour as the system was not baked. However, longer pumping will further reduce the pressure.

All flanges up to 600 mm diameter are sealed with copper gaskets. Flanges bigger than that, i.e. 1000 mm at the doors of the tanks, 1500 mm at the tube sections and 3000 mm at the lids of the tanks, are sealed with two Viton O-rings each. The gap in between these two O-rings is pumped by another scroll pump. This scheme of differential pumping allows us to reach a low residual gas pressure while keeping the cost for the vacuum system at a tolerable level.

The two scroll pumps, for backing and differential pumping, are installed in a separate pump room. The scroll pumps are set up on a double-stack vibration isolator made of two granite plates (about 200 kg each) and two layers of Sorbothane hemispheres. The pumps themselves are also isolated by another layer of Sorbothane dampers.

The vacuum system is fully installed and operational since May 2009.

3. Isolation tables

The isolation tables are the mechanical interface between the vacuum system and the suspension systems supporting the main and ancillary optics of the interferometer. As the experimental hall is located in downtown Hannover, surrounded by roads and tramways, anthropogenic noise is the main source of seismic disturbances measured in the lab. Vertical and horizontal displacements up to 300 nm (rms value) above 1 Hz have been measured on the hall floor during daytime. The optics suspensions have their resonances in the 1–10 Hz band and therefore, it is important to reduce the amplitude of the motion of the optical tables at those frequencies to avoid overloading the optics control systems causing noise injection and limiting the sensitivity of the experiments.

The optical tables consist of a welded stainless-steel honeycomb structure of dimensions $1750 \times 1750 \times 400$ mm. Each table is supported by a seismic attenuation system (SAS). The SAS is a six-degree-of-freedom vibration isolator, providing the necessary shielding from the ground microseismic noise which is the main environmental source of disturbance in the frequency range from 0.1 Hz to 100 Hz. The SAS is a completely custom made device capable of providing vibration isolation factors not achievable in a single stage, to our knowledge, by any other existing commercial or laboratory developed system. Its design is derived from a prototype device (HAM-SAS: horizontal access module seismic attenuation system) built by Caltech in 2006 in the framework of the R&D for the gravitational wave detector AdvLIGO [5]. Attenuation factors larger than 70 dB at 10 Hz are expected in both the vertical and horizontal direction.

The seismic attenuation of the SAS is obtained passively by using mechanical oscillators to attenuate vibrations, as second-order low-pass filters, above their natural frequency. Each table sits on three vertical vibration isolators (named filters) which provide mechanical compliance along the vertical, pitch and roll degrees of freedom. The tables operate with very low natural frequencies, 0.05 Hz in the horizontal and 0.1 Hz in the vertical direction, respectively, allowing large vibration suppression ratios to be achieved. The isolation goal is 60 dB at 3 Hz in both directions.

Each filter consists of a tunable spring made of a crown of curved cantilever blades which are compressed against each other: the constrained radial stress creates an anti-spring effect (geometric anti-spring) that leads to a very low effective stiffness in the vertical direction at the nominal load [6]. Natural frequencies down to 0.2 Hz can be obtained by mechanical adjustment of the compression rate; even longer natural periods can be achieved by applying positive feedback (electronic anti-spring). The inertia of the blades limits the minimum vibration transmissibility to −60 dB, which can be improved to −80 dB by using the built-in compensators (so-called magic wands).

The three filters are mounted on a rigid plate supported by three inverted pendulum (IP) legs: very low natural frequencies (around 0.05 Hz) are achieved for the horizontal (*X*, *Y*) translational modes and for the yaw mode. This is done by suitably sizing the IP bottom flexures to compensate for the load gravitational torque which drives the system towards instability [7]. The short flexure hinges at the top of the IP allow the filter plate to wobble in the horizontal plane preventing its pitch/roll movement. The inertia of the legs would limit the IP minimum vibration transmissibility to −70 dB. However, by tuning the built-in counterweights up to −90 dB can be achieved.

The amplification of the seismic noise at the SAS resonances would make the motion of the tables uncomfortably large at low frequencies. Hence, the attenuators are instrumented with a range of sensors (linear variable differential transformers and horizontal accelerometers) and voice-coil actuators to perform electronic modal damping. The SAS control is based on rather elementary feedback filters and is limited to a few Hertz bandwidth. The natural completion to the local SAS action is the global inter-table distance and attitude stabilisation using the signals from the suspension platform interferometer (SPI).

The isolation tables are scheduled for installation in spring 2010.

4. Suspension platform interferometer

Even though the optical tables are highly isolated and separated by merely 12 m, there will be some residual differential motion between them. This relative motion will be sensed by the suspension platform interferometer. The obtained signals can then be used to apply the according feedback to the tables via voice-coil actuators.

The SPI consists of a set of three heterodyne Mach–Zehnder interferometers. One of them is used as a reference interferometer, and the other two measure the differential motion between the optical tables. The equal arm length reference interferometer is set up on the central isolation table. It is used to subtract all laser noise that came in on the way between the laser and the optical setup inside the vacuum system. The two measurement interferometers have each a short arm (about 10 cm) and a long arm (about 22 m). This large mismatch in arm length leads to strong coupling of laser frequency noise. As the measurement frequency is very low, a molecular iodine reference was chosen to stabilize the laser frequency to, thus allowing operation of the SPI at the required level.

The optical signals are obtained with a set of quadrant photodiodes which are read out by a LISA pathfinder-style phasemeter. The phasemeter itself is based on FPGAs (field programmable gate arrays) to allow fast processing of the signals. The data from the phasemeter are sent via an enhanced parallel port to the phasemeter interface (PMI). The PMI provides a microcontroller-based ethernet interface, designed to connect the SPI to our digital control system (CDS) with the required low latencies.

All relevant optical components of the SPI are bonded onto low-expansion glass plates to avoid thermal drifts. The design goal for the SPI is to reduce the differential motion between the tables to less than 100 pm $\mathrm{Hz}^{-1/2}$ and 10 nrad $\mathrm{Hz}^{-1/2}$ at 10 mHz. These goals are set by experiments to be conducted for the LISA space-borne gravitational-wave detector and geodesy missions within the QUEST cluster of excellence.

For the full details and current status of the SPI setup please refer to [8].

5. Suspensions

The ambitious goals of the AEI 10 m prototype interferometer impose strict limits on the noisy motions of the measurement optics. As in all current (and planned) full-scale interferometric detectors, the optics will be suspended as the final stages of (multiple-cascaded) pendulums, where the natural frequency-filtering effect is used to isolate the optics from seismic motions at frequencies above the pendulum resonances.

There will be three classes of suspensions required for the first set of experiments: those forming the frequency-reference cavity, the main interferometer optics and ancillary optic suspensions.

5.1. Frequency-reference cavity optics

The first optical setup to be implemented in the prototype will be a suspended frequency-reference cavity, used to suppress laser frequency noise. This will consist of a three-mirror, high-finesse triangular-ring cavity. The mass of the optics was chosen to be 850 g, balancing the reduction of radiation pressure induced noise with the desire to have a compact suspension. The suspension system will comprise three stages of similar mass. The final silica optic will be suspended from an intermediate aluminium mass by thin stainless steel wires: 55 μm diameter wire will be used to both lower the stage's vertical resonance frequency to 20 Hz and raise the first violin mode to 400 Hz, keeping these features out of the measurement band of the main interferometer.

The intermediate stage is connected to the uppermost stage via stainless steel wires attached to cantilever springs (made of maraging steel) mounted on the upper stage. These springs help to lower the overall vertical resonance frequencies, thus reducing additional noise contributions from vertical-to-horizontal noise coupling. The upper stage is then used to provide local eddy-current damping of pendulum resonances, as well as providing a platform for the application of alignment and drift control signals through adapted Bosem-style magnet and coil assemblies. Finally, the uppermost stage is joined to a suspension cage structure by two additional cantilever blades.

5.2. Interferometer optics

To reach SQL limited sensitivity, high laser power and low mirror masses are required. A mirror mass of 100 g should allow this goal to be reached while still allowing a practical—though challenging—suspension design to be realized. In order to sufficiently isolate the optics, a triple-stage suspension (with two stages of vertical isolation) will be needed. The final stage will comprise a monolithic all-silica structure with the optics suspended from four 20 μm fused silica filaments to reduce suspension thermal noise.

5.3. Ancillary optics

Other optics are required to steer and point the laser beam into and out of the main interferometer and the vacuum system. Due to the excellent isolation provided by the isolated optical tables and the SPI system, such ancillary optics can be isolated with relatively simple single-stage suspensions systems, with no additional vertical isolation.

6. Laser system

We will use a 35 W solid-state laser as the light source for the AEI 10 m prototype interferometer [9]. In this laser system the light of a commercially available 2 W Nd:YAG seed laser passes through four Nd:YVO4 crystals in an amplifier configuration. Each of these crystals is pumped by a 400 μm diameter fibre-coupled laser diode with a nominal power of 45 W and a numerical aperture of 0.22. To increase the lifetime of the diodes, the pump power is set to 33 W during nominal operation. The 3×3 mm cross section laser crystals consist of a 2 mm undoped and an 8 mm long doped Nd:YVO4 region (0.3 at.%). The undoped region was bonded to the crystal to reduce thermal stress at the surface where the pump beam enters. The laser crystals are wrapped in thin indium foil and mounted inside a water-cooled copper block.

The 2 W NPRO (non-planar ring oscillator) beam is amplified to a power level of 35 W when passed through the four laser heads. The wavelength matching between the Nd:YAG and the Nd:YVO4 system is done by temperature tuning of the NPRO. The relative power noise (RPN) of the 35 W front end is identical to that of the NPRO at Fourier frequencies below 50 Hz and exceeds it by a factor of up to 5 for frequencies in the audio band. The spatial beam quality of the NPRO (97% TEM_{00} mode content) is only slightly degraded by the amplification process; 95% of the power of the 35 W front end was measured to be in the TEM_{00} mode. Passing the beam through a photonic-crystal fibre and a subsequent rigid-spacer, pre-modecleaner cavity of moderate finesse ($\mathcal{F} \approx 500$) will further improve the spatial profile and reduce the beam pointing fluctuations.

7. Frequency stabilisation

The frequency fluctuations of the 35 W laser are at the same level as those of the 2 W NPRO seed. Owing to the fact that we will use mirrors of only 100 g for the main interferometer, radiation-pressure noise will prevent us from using the interferometer itself to provide a frequency reference. Hence, we will use a dedicated suspended optical resonator for the laser frequency stabilisation. This frequency-reference cavity consists of three mirrors that form a triangular-ring resonator of about 24.6 m round-trip length. Two mirrors will be placed on the central optical table while the mirror at the small angle of the triangle will be set up on the south table.

The sum of all displacement-noise equivalent fluctuations in this system needs to be suppressed to 10^{-17} to 10^{-19} m Hz$^{-1/2}$ from 20 Hz to 1 kHz. This level is ten times smaller than the strict requirement, allowing us a sufficient safety margin. The total noise of the reference cavity will be dominated by seismic motion, thermal noise and shot noise in the low, middle and high frequency region, respectively. As described above, a triple-cascaded pendulum suspension system was chosen to isolate the mirrors from seismic motion. The relevant suspension design parameters (e.g. wire thickness and length), as well as substrate material, are chosen to minimize thermal noise. Optical design parameters (e.g. laser power inside the cavity, overall reflectivity of the cavity) as well as the mirror mass (850 g) are tuned to optimize shot noise performance and radiation pressure noise. A small amount of light (130 mW) from the 35 W laser will be picked off and injected into the reference cavity. As the cavity finesse is high ($\mathcal{F} \simeq 7300$) the circulating power is large enough to optimize the shot noise limited signal-to-noise ratio, but small enough that the radiation pressure noise from classical intensity noise will not be limiting.

For the control of the cavity length and thus, of the laser frequency the Pound–Drever–Hall scheme is applied. Angular motions will be revealed via differential wave-front sensing. At frequencies well above the pendulum resonances, the length of the free reference cavity

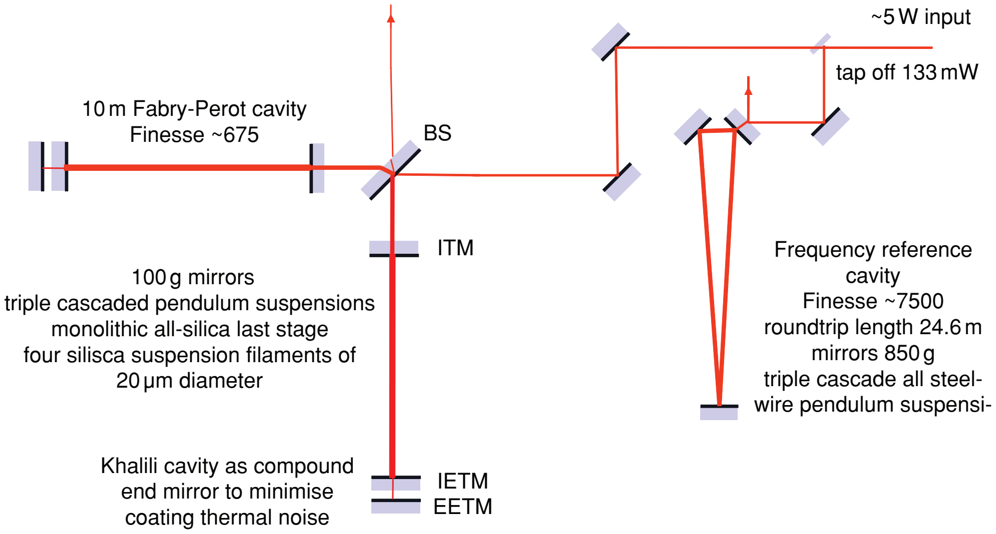

Figure 2. The basic optical layout for the first round of experiments in the AEI 10 m prototype facility. The frequency reference cavity and the main interferometer along with the most relevant design parameters are shown. Note that only 5 W input power will be used for the first experiments.

is used as a frequency reference. Below these frequencies the cavity length is locked to a molecular iodine reference. As such, the laser frequency will be stabilized to the length of the reference cavity at all relevant Fourier frequencies.

8. Control and data system

To collect and digitize data from the many sensors and to control the interferometer, we use the control and data system (CDS) software developed by LIGO. The CDS is used for both collecting science data and data from ancillary systems such as environmental monitoring devices. In the initial configuration the AEI 10 m prototype interferometer requires about 500 channels forming multiple-input multiple-output control loops. Digital-to-analogue conversion (DAC) and analogue-to-digital conversion (ADC) are performed using 16 bit fully differential PC-expansion cards with either PCI-X or PCIe bus connection and a maximum sampling frequency of 256 kS s^{-1} per channel. However, the standard sampling frequency is 64 kS s^{-1}. For the most sensitive channels, we use 18 bit cards in order not to be limited by noise from the DAC/ADC. The front-end machines are standard Opteron- or Xeon-based servers.

As control and data acquisition has to be performed in real-time, special care has to be taken to choose low-latency hardware. As standard gigabit ethernet possibly imposes high latencies, we use fibre-based Myrinet connections for low-latency communication. The CDS software is based on a real-time enabled Linux operating system. Operator control screens and channel access are realized with the experimental physics and industrial control system (EPICS).

The software architecture on our CDS system, namely the real-time code generator, allows us to use Matlab/Simulink or C-code to design a circuit, which is then used to build a real-time

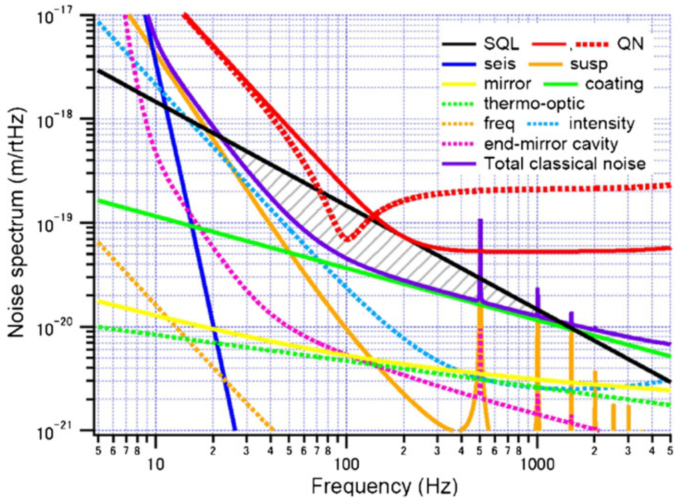

Figure 3. The design sensitivity of the AEI 10 m prototype interferometer. The black straight line is the SQL, the red solid curve is the sum of quantum noise, the blue solid line is the sum of all classical noise sources. The dashed area inbetween the sum of classical noise and the SQL is the QND regime that we hope to be able to explore by applying e.g. the back-action evasion technique (red dashed curve).

kernel module. This module is then loaded onto a real-time enabled front-end computer and can be controlled via the EPICS control channels and screens.

9. Optical layout and design sensitivity

The main instrument in the AEI 10 m prototype interferometer facility is a 10 m Michelson interferometer with Fabry–Perot cavities in the arms (figure 2). The arm cavity finesse will be about $\mathcal{F} \simeq 675$. However, there will be no recycling techniques such as signal- or power-recycling in the first round of experiments.

A speciality of our design is the use of Khalili cavities as compound end mirrors to minimize coating thermal noise [10]. The end test mass in each arm consists of a Fabry–Perot cavity locked to anti-resonance for the carrier light. The input end test mass (IETM) will carry only two coating doublets (51% power reflectivity) while the end end test mass (EETM) will have a coating stack made of 15 doublets to form a highly reflecting mirror. As a result, the IETM itself introduces only moderate coating thermal noise. The higher level of coating thermal noise originates from the EETM, but this is reduced by the transmissivity of the IETM. In this way, the overall coating thermal noise from the compound end mirror can be reduced by a factor of about 3 when compared to a conventional single mirror of the same reflectivity. Thus, the contribution from the input test mass dominates the mirror coating thermal noise. The Khalili cavities will be locked independently of the main interferometer via the injection of an offset phase-locked sub-carrier beam from the rear side.

The design sensitivity of the main interferometer is given in figure 3. The sensitivity is shaped such that a gap between the sum of the quantum noise and the sum of all classical noise contributions opens up at around 100–200 Hz. Around this sweet spot of sensitivity a factor of about 3.3 separates the two curves. This gap will later allow us to achieve a sensitivity beyond the SQL. Such a sensitivity can be reached when injecting squeezed states of light at the appropriate orientation of the squeezing ellipse, or when applying the scheme of back-action evasion read out [11].

10. Conclusion

We have presented the design and current status of the AEI 10 m prototype interferometer. It aims to achieve sub-SQL sensitivity by use of advanced techniques, such as Khalili cavities as compound end mirrors, an advanced passive and active isolation system, monolithic mirror suspensions, a well-stabilized high-power laser system and the injection of squeezed light or application of back-action evasion techniques.

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