EXPERIMENTAL APPROACHES FOR THE EINSTEIN TELESCOPE

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Interferometric gravitational wave detectors currently under operation have reached their design sensitivities and will by upgraded to their second generation having ten times more sensitivity. It is expected that these instruments will detect gravitational waves directly for the first time and thus opening the era of gravitational wave astronomy. The Einstein Telescope design study - funded by the European Commission - investigates the technical and scientific challenges for a third generation of gravitational wave detectors that will have a 100 times better sensitivity compared to the first generation. This contribution summarises selected experimental approaches for the Einstein Telescope and will discuss challenges for the future research within this vital field of precision measurements.

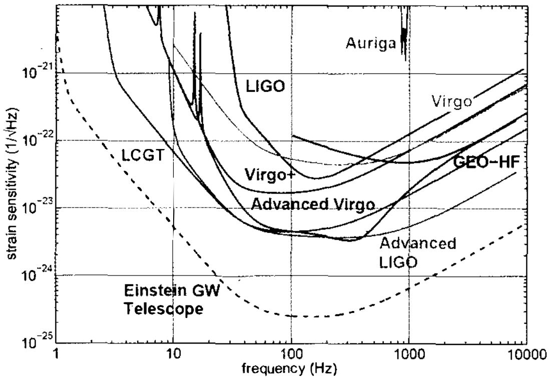

Figure 1: Overview of the sensitivities of the fist (LIGO, Virgo, Virgo+) and second generation (Adv. LIGO, Adv. Virgo, GEO-HF, LCGT) GW detectors compared with the Einstein Telescope. Additionally, the typical sensitivity for a bar detector (Auriga) is given as well.

1 Introduction

The interferometric gravitational wave detectors - LIGO [1], Virgo [2], GEO600 [3] and TAMA [4] - currently under operation have reached their design sensitivity within a wide frequency range from about several 10's of Hz up to a few kHz. They have demonstrated an operational regime in a world wide network having a large duty cycle. While during their operational time no gravitational wave signal was detected the experimental data has been used to study several astronomical sources allowing the determination of unknown properties [5,6].

Currently, these detectors - which are called the first generation - are upgraded to a second generation. These detectors will have a ten times larger sensitivity for gravitational waves. This network of second generation detectors including Advanced LIGO [7], Advanced Virgo [8], GEO-HF [9] and LCGT [10] is expected to detect gravitational directly when coming up online in 2014/15. The direct observation of gravitational waves will open a new window to the universe exploring new physics of astronomical objects and the universe itself. Novel experimental and technical approaches have been developed in order to increase the detectors sensitivity. Their potential has been demonstrated in the first generation detection and were included in the design of the second generation detectors. Amongst them are important technologies for the Advanced Detectors as for example the monolithic fused silica suspension that have has pioneered in GEO600 [11,12,13] or the Squeezing Technique [14,15] that allows to overcome quantum limitations.

Beyond the Advanced Detector generation there are already efforts that focus on a further enhancement of the detectors. The Einstein Telescope (ET) design study [16,17] is a European Commission funded project to investigate a conceptual design for a future GW observatory that included novel technologies needed for a long time operation for two to three decades.

A summary of the scientific potential of the Einstein Telescope can be found e.g. in [18,19].

2 Sensitivity considerations

The focus of the ET Design Study was the demonstration of a conceptual design of a GW observatory that has ten times better sensitivity compared to the Advanced Detectors within a wide range of frequencies (see Fig. 1).

The main sensitivity limitations of a GW detector are:

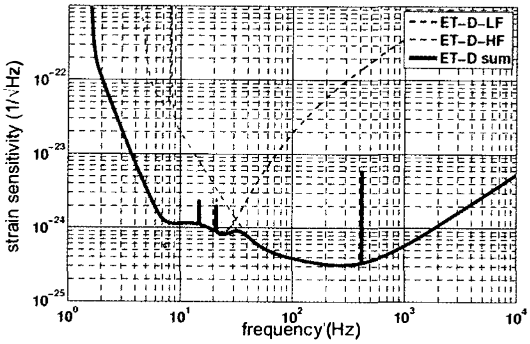

Figure 2: Xylophone design of the Einstein Telescope. The low frequency part (LF) of the sensitivity curve is realised with a low laser power interferometer operating at cryogenic temperatures while the high frequency (HF) part is covered by a room temperature interferometer with a circulating laser power of up to 3 MW.

- at low frequencies: seismic noise, thermal noise of the suspension elements, radiation-pressure noise,
- in the mid-frequency range: thermal noise of the optical components,
- at high frequencies: photon shot noise of the laser light.

All these noise contributions have been carefully studied and influenced the design of the second generation detectors. This design is based on the available infrastructure from the first generation (e.g. detector site, vacuum tubes, etc.). In contrast, for the ET design study the site selection and the design of the infrastructure was included into the conceptual design allowing more flexibility and a further reduction of these noise contributions by novel techniques.

In order to overcome the different noise limitations different techniques are required. While for the high frequency part high laser powers of up to 3 MW are preferable the low and mid frequency part of the sensitivity curve requires the use of cryogenic techniques to reduce thermal noise from the suspension elements as well as the optical components [20]. These two approaches are contradictory. Initial estimates have shown that a cryogenic operation of the optical components at around 20 K is not feasible with circulating laser powers in the MW range.

The solution was the suggestion of a design that uses two different interferometers - the so-called Xylophone design [21,22]. The low frequency part of the sensitivity curve is realised with a low laser power interferometer with optics operating at around 10-20 K. The high frequency part is covered with a high power interferometer with up to 3 MW laser power operating at room temperature and is based on the sophisticated techniques that have been developed for the Advanced Detectors.

3 Material Issues and Thermal Noise

3.1 Optical Materials

The reduction of thermal noise of the optical components and the suspension elements is realised by means of utilising cryogenic temperatures of about 10 K for the low frequency detector. Brownian thermal noise [23,24] of a component is dependent on its temperature and its mechanical loss. Both values should be as low as possible in order to get a low Brownian thermal noise level. The first and second generation of GW detectors use fused silica as the test mass materials as well as (in parts) for suspension elements. This material provides a low mechanical loss as well

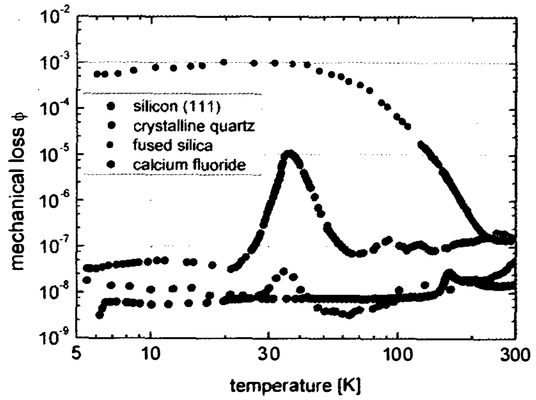

Figure 3: Comparisson of the mechanical loss of different materials at low temperatures.

as excellent optical properties. It is known that amorphous materials like fused silica have a high level of mechanical loss at cryogenic temperatures (see e.g. [25,26]). Thus, different materials have to be used for a low thermal noise operation. Different materials have been discussed in the past for cryogenic applications. Among them sapphire, calcium fluoride and silicon have been studied in detail. Sapphire is the material of choice for the LCGT detector [10]. Calcium fluoride showed low mechanical losses[27,28,29] - however, the expected dimensions of the ET main optics of about dia. 50 cm and a thickness of 45 cm rule this material out. It is currently not available in such large dimensions and it cannot be foreseen that this will change within the next years. In contrast silicon also shows very low mechanical losses at cryogenic temperatures [30]. Currently, the semiconductor industry is pushing for large single crystals due to their demand for large wafers. Thus, silicon has been proposed as an optical material for GW detectors for a long time [31,32,33].

The total thermal noise budget of an end mirror of the Einstein Telescope is shown in Fig. 4. The main contribution of the total thermal noise is the Brownian thermal noise of the coating

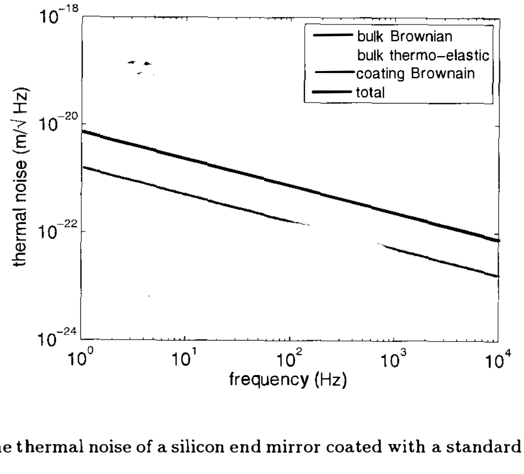

Figure 4: Summary of the thermal noise of a silicon end mirror coated with a standard tantala:silica HR multilayer.

material. A detailed study of the mechanical loss of different coating materials is currently ongoing[34,35,36,37] in order to minimise the coating contribution.

3.2 Suspension Materials

A monolithic suspension technique based on fused silica as the material and hydroxide-catalysis bonding for jointing materials has been adapted for the Advanced Detectors[7,38,39,40]. As discussed previously fused silica cannot be used in cryogenic applications due to its large mechanical loss. Additionally to the low thermal noise design the suspension elements of the cryogenic optics needs to fulfill a second duty: It has to extract the residual heat from the mirror that is caused by optical absorption of the optics. Thus, a material with high thermal conductivity is preferable. Silicon and sapphire are both materials that show low thermal noise at cryogenic temperatures and a high thermal conductivity. Sapphire is currently investigated as the suspension material for the LCGT detector. Silicon has been studied as a suspension material for the Einstein Telescope. Low mechanical loss as well as the possibility to fabricate strong and reliable bonds based on the hydroxide-catalysis technique have been shown for silicon[41,42].

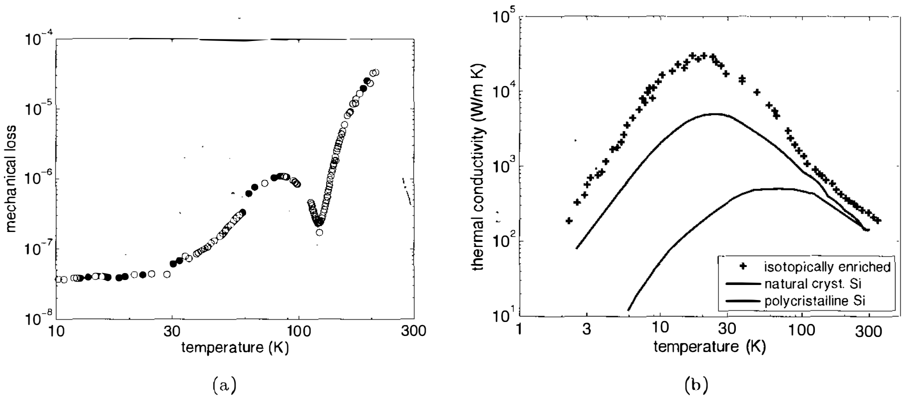

Figure 5: Mechanical loss (a) and thermal conductivity (b) of silicon as a suspension material.

These material properties allow a similar monolithic design to the Advanced Detectors. The last stage of the suspension is proposed to be fabricated in monolithic way allowing low thermal noise and high thermal conductivity at cryogenic temperatures (see Fig. 5). Details of the suspension design and the cryogenic aspects can be found in[18,43].

4 Optical Layout, Infrastructure and Site Selection

A Michelson-based detector with a triangular shape[44] was identified to give the optimum solution regarding scientific output, future flexibility and construction efforts. Each corner station will be equipped with one detector (which consists of two interferometers - LF and HF, see Fig. 6). The observatory will be placed underground in order to reduce seismic disturbances as much as possible. The arm length of the interferometers was fixed to a length of 10 km. The length is based on a trade-off study between scientific benefits and the construction costs. This trade-off was a central point of the Einstein Telescope Design Study[18]. The conceptual design study contains detailed analyses of the scientific benefits and the costs of the instrument and its potential configuration.

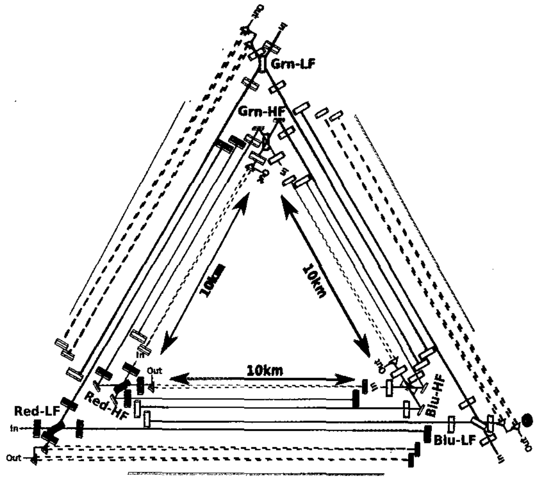

Figure 6: Triangular shape of the proposed Einstein Telescope design. Each corner station contains two interferometers - one cryogenic interferometer for the low frequency part and one high laser power interferometer for the high frequency part of the spectrum.

Several potential candidate sites have been studied in detail regarding their local seismic noise, their compositions of the soil and the possibility to construct the infrastructure for the proposed observatory.

Different optical techniques are within current investigations for implementation in third generation GW detectors. One example are Laguerre Gauss (LG) modes as a replacement for the Gaussian laser beams[45]. Due to the different averaging of the mirror surface fluctuations the LG modes provide a low level of thermal noise. Compared to other non-Gaussian beam profiles - like Mexican hat or flat-top profiles - the LG beams are compliant with spherical optics as currently in use.

5 Summary

A selection of experimental approaches for a European third generation gravitational wave detector has been presented. The full design study document can be found online at www.et-gw.eu describing the experimental approaches as well as scientific benefits of such a detector more in detail.

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